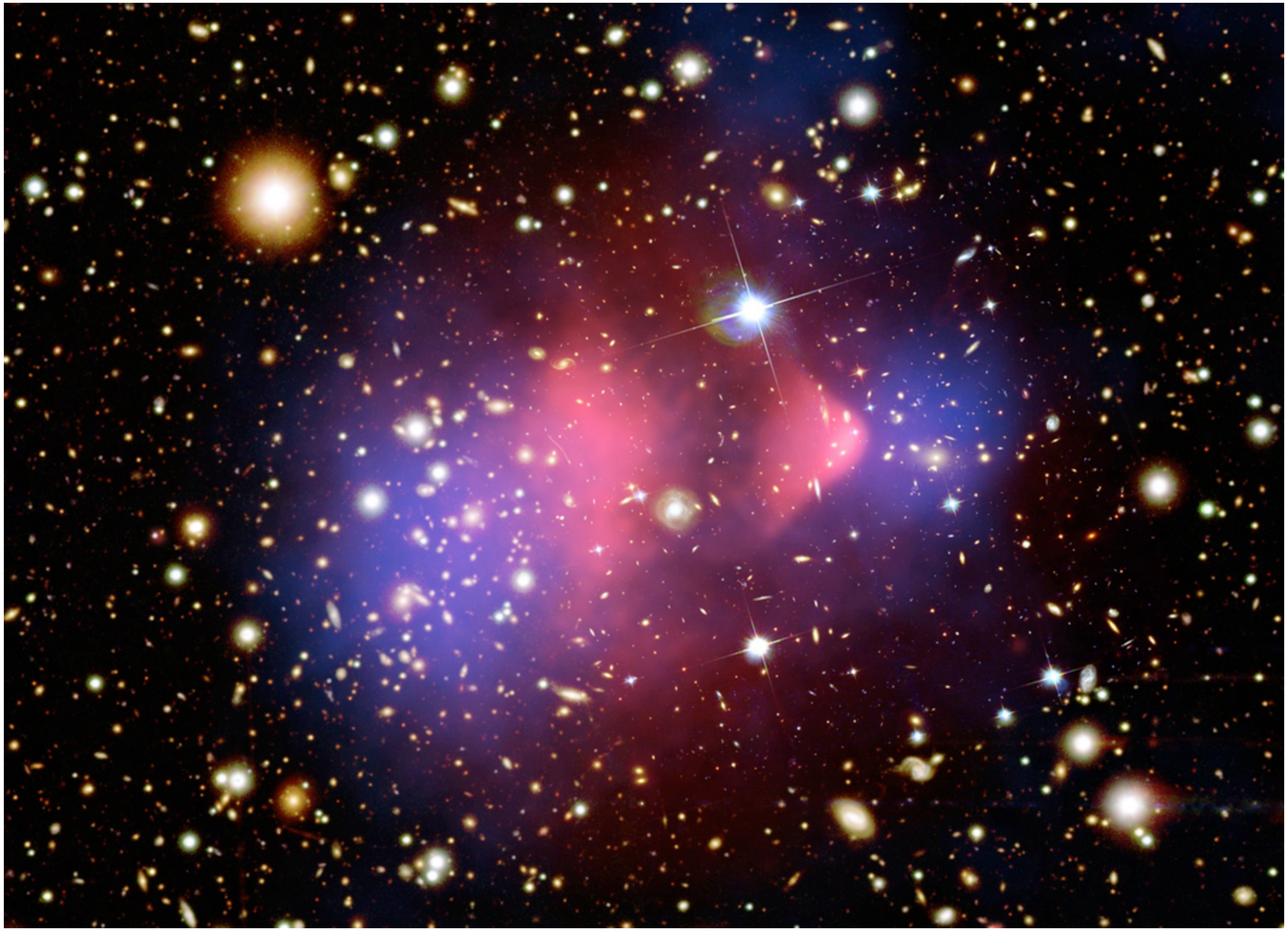
New Directions in Searching for the Dark Universe

Surjeet Rajendran,
UC Berkeley

Dark Matter

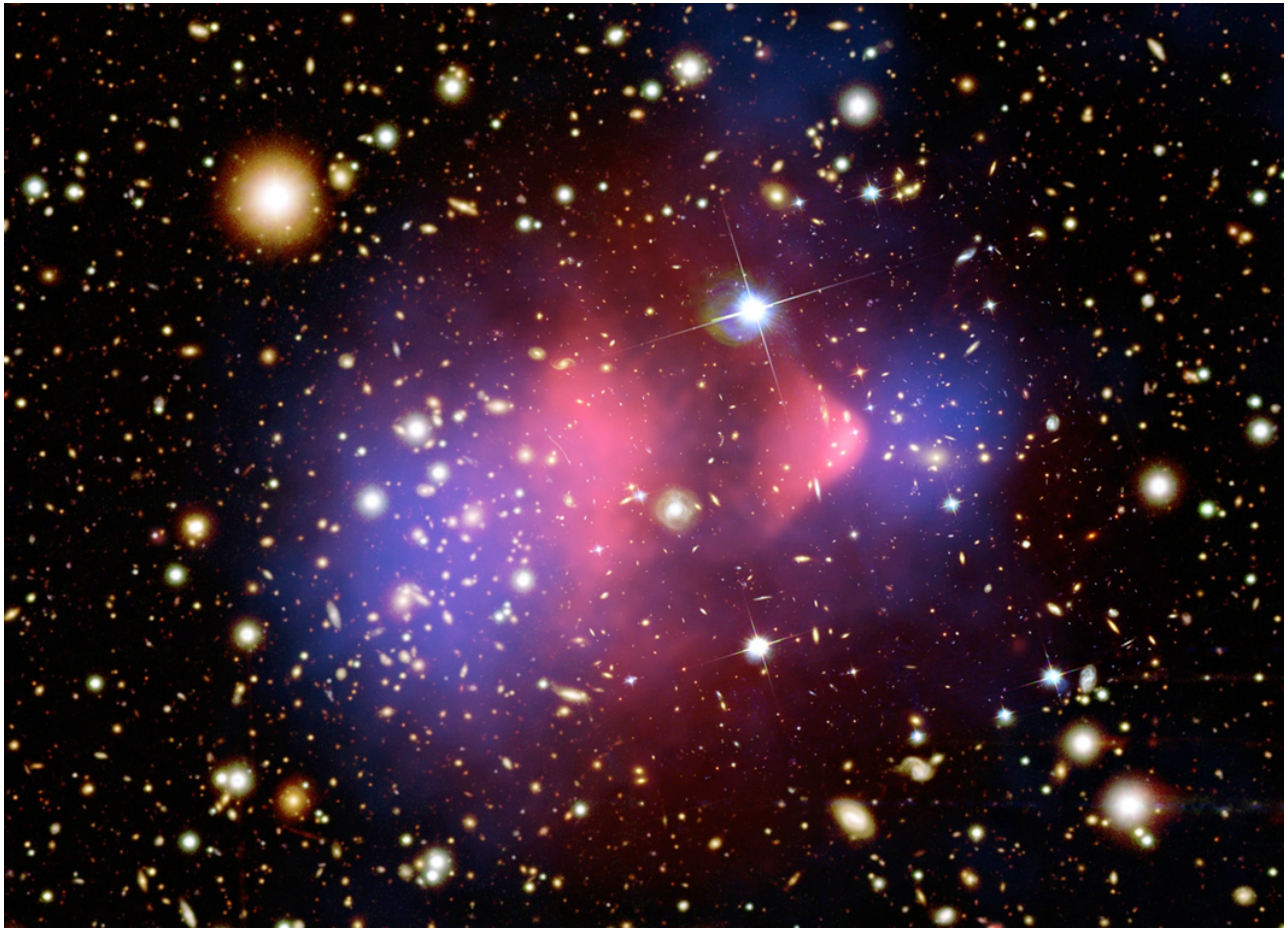
Dark Matter



A New Particle

Non gravitational interactions?

Dark Matter



A New Particle

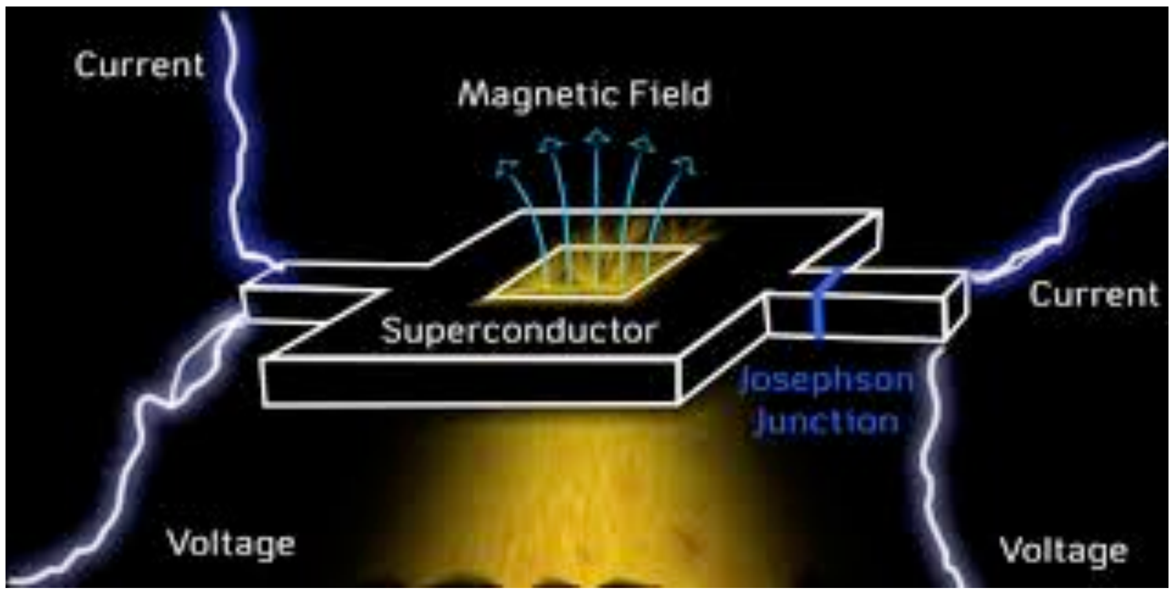
Non gravitational interactions?

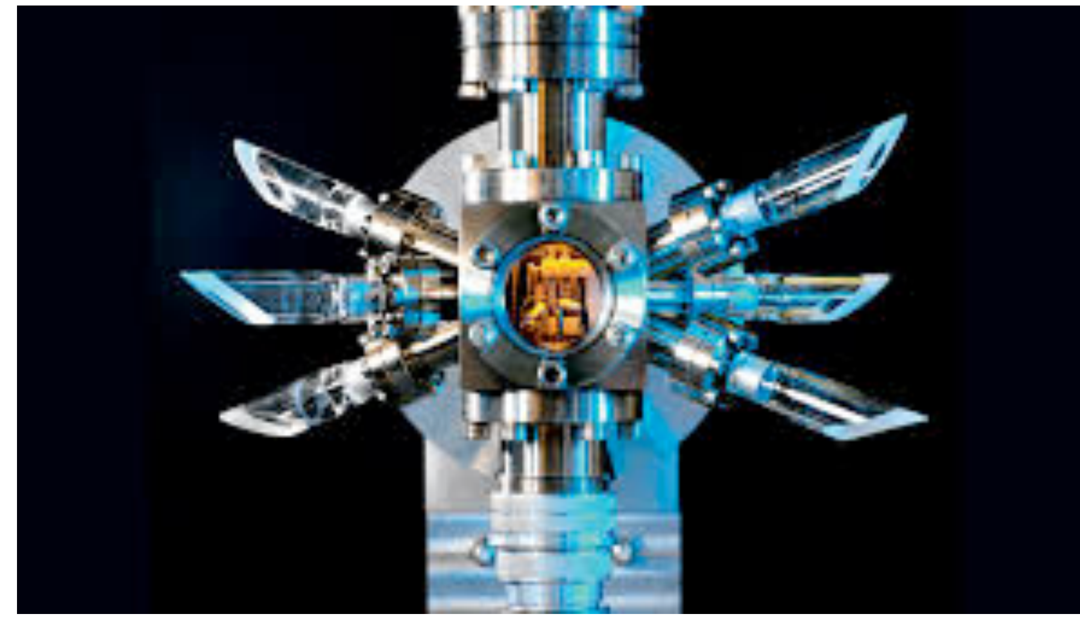
How do we detect them?

Weak effects. Need high precision

Precision Instruments

Impressive developments in the past two decades





$$\text{Magnetic Field} \lesssim 10^{-16} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$$

(SQUIDs, atomic magnetometers)

$$\text{Accelerometers} \lesssim 10^{-13} \frac{\mathrm{g}}{\sqrt{\mathrm{Hz}}}$$

(atom and optical interferometers)

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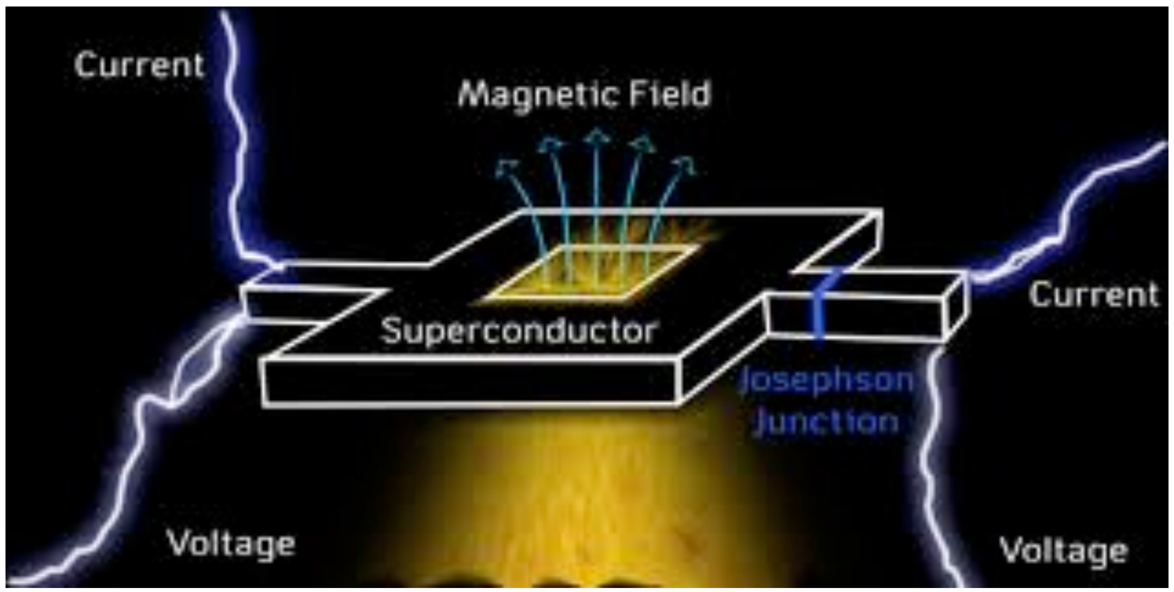

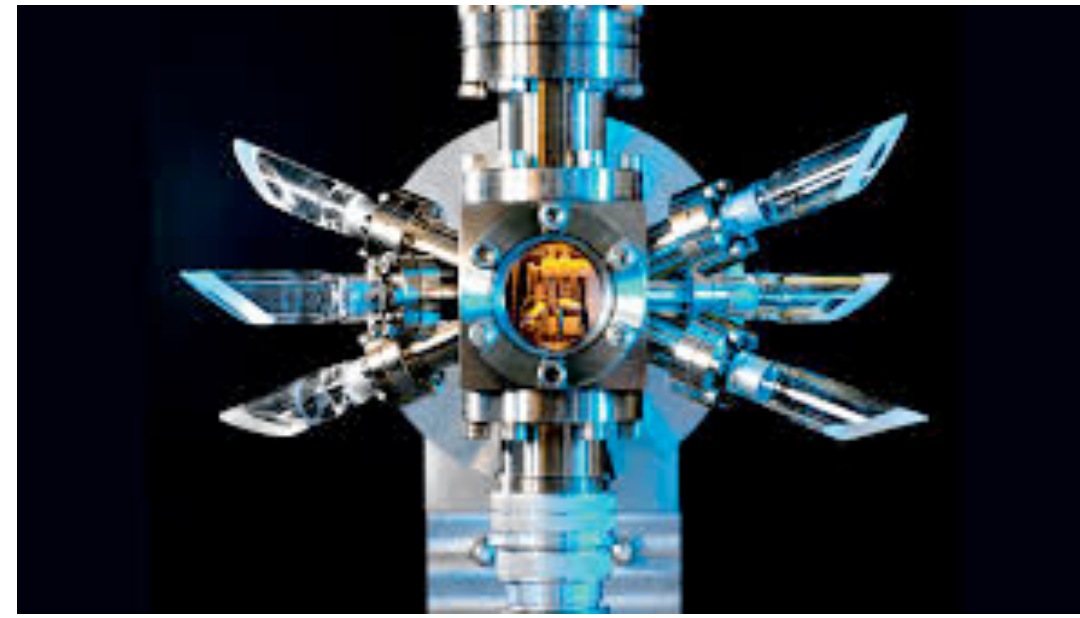

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Rapid technological advancements

Use to detect new physics?

Outline

1. Brief Theory Overview

2. Axion Detection with Nuclear Magnetic Resonance

3. Dark Photon Detection with Radios

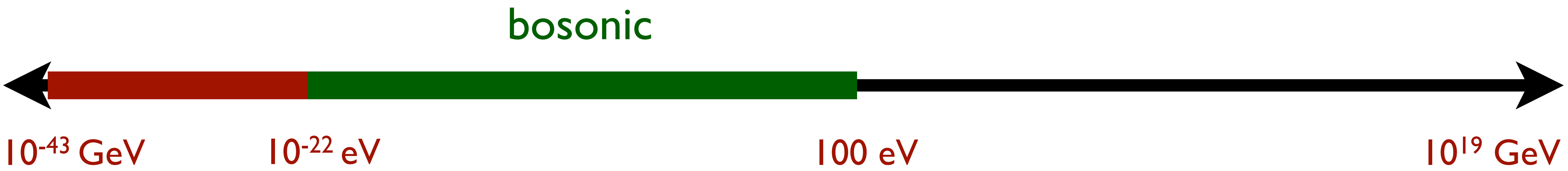
4. B-L Gauge Boson with Accelerometers

5. Conclusions

The Dark Matter Landscape

10^{-43} GeV 10^{19} GeV

The Dark Matter Landscape



Fit in galaxy

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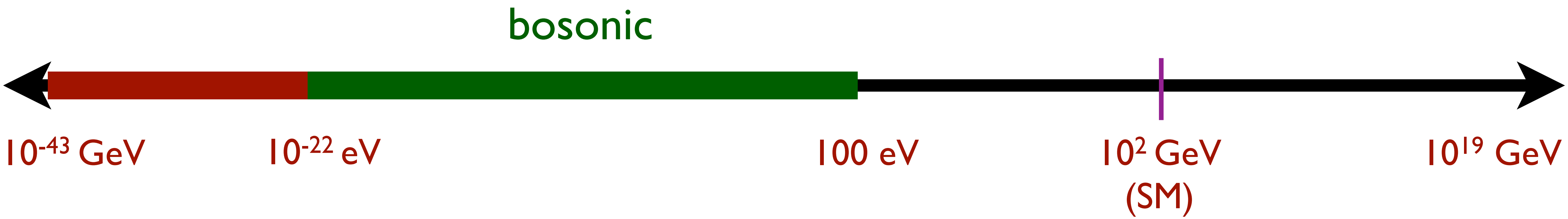

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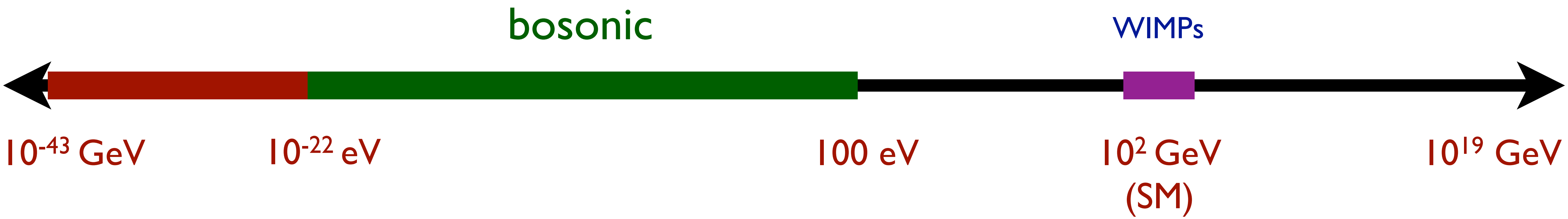
Standard Model scale ~ 100 GeV

The Dark Matter Landscape



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One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

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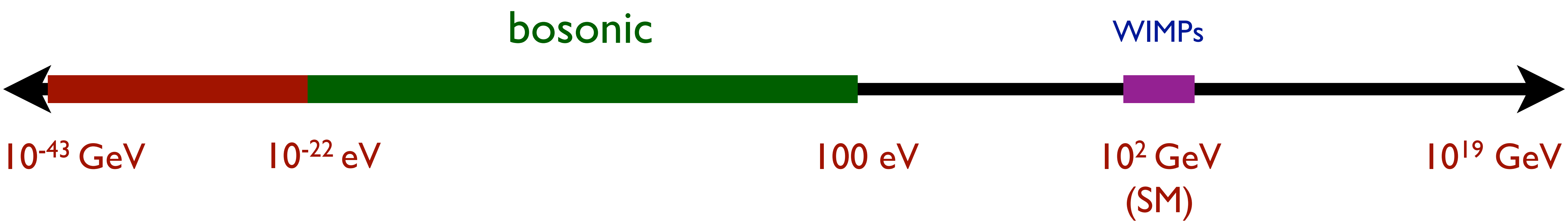

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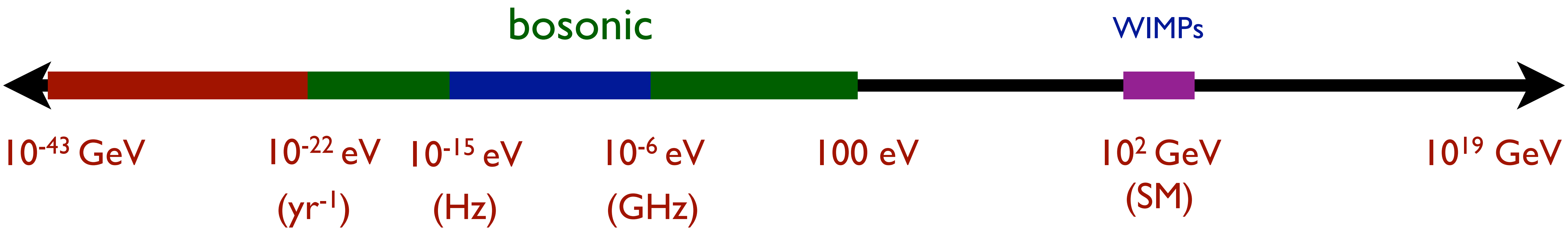

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How do we search for them?
This Talk: Bosons between GHz - Hz
Range includes popular candidates such as the QCD axion

Bosonic Dark Matter

Photons

$$\vec{E} = E_0 \cos(\omega t - \omega x)$$

Detect Photon by measuring time varying field

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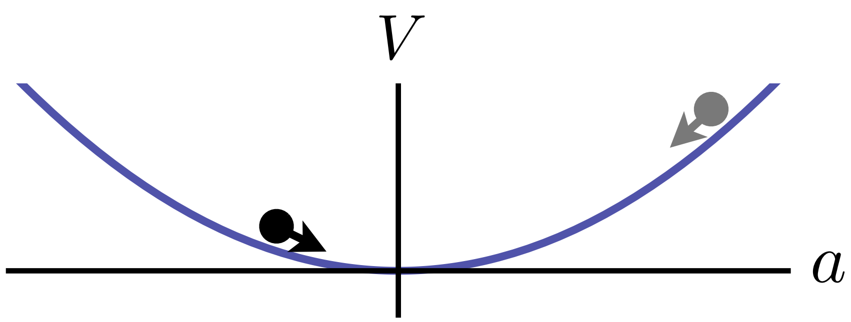
Dark Bosons

Early Universe:
Misalignment Mechanism



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

Spatially uniform, oscillating field

$$m_a^2 a_0^2 \sim \rho_{DM}$$

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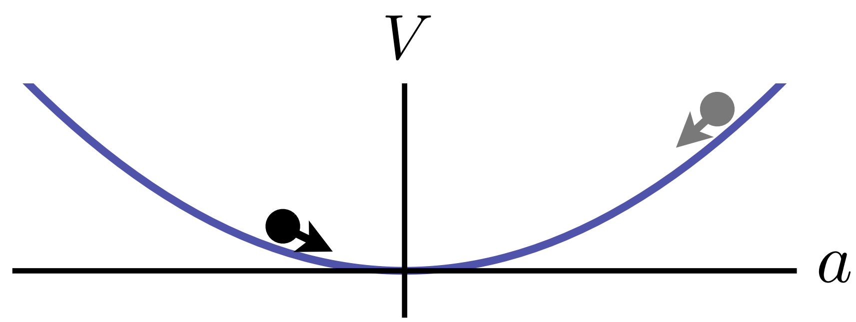

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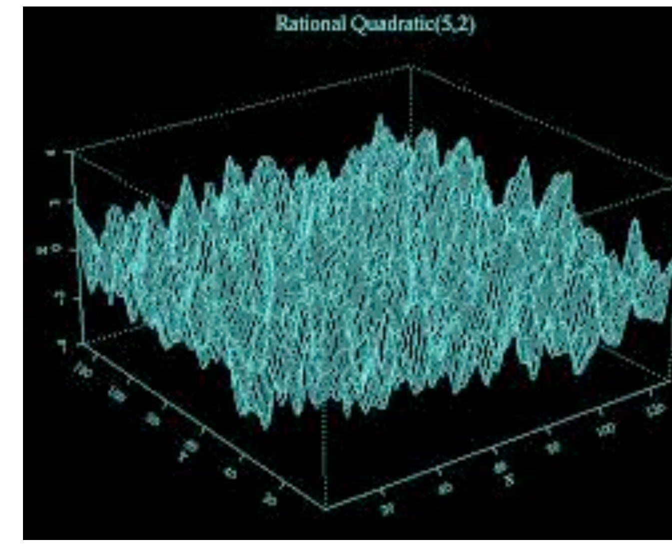
Today: Random Field



Correlation length $\sim 1/(m_a\, v)$

Coherence Time $\sim 1/(m_a\, v^2)$ ~ 1 s (MHz/m_a)

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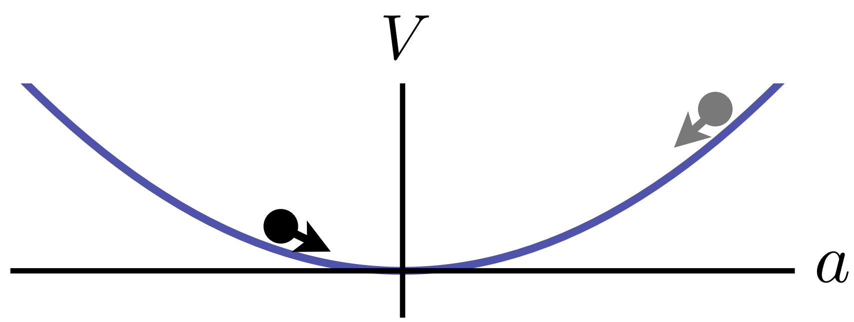

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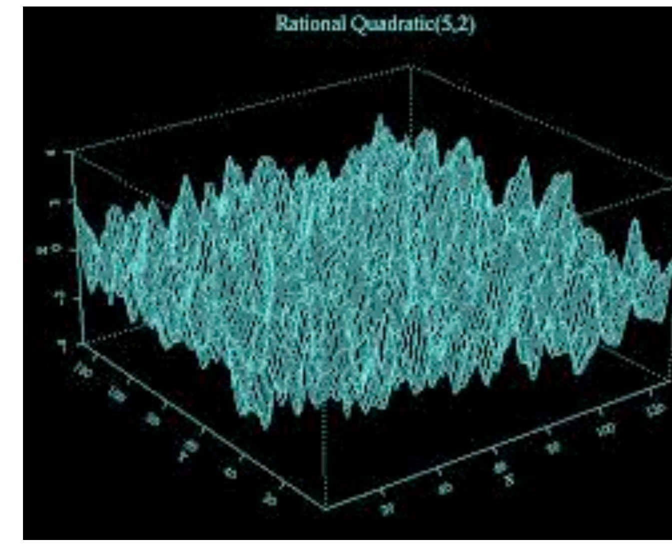

Correlation length
~ $1/(m_a\ v)$

Coherence Time
~ $1/(m_a\ v^2)$
~ 1 s (MHz/m_a)

Detect effects of oscillating dark matter field

Resonance possible. Q ~ 10^6 (set by v ~ 10^{-3})

What kind of Bosons?

Naturalness. Structure set by symmetries.

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Spin 0

Axions and other goldstone bosons

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Electromagnetism

$$\left(\frac{a}{f_a} F\tilde{F}\right)$$

Nuclear Force

$$\left(\frac{a}{f_a} G\tilde{G}\right)$$

QCD Axion

Nuclear Spin

$$\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$$

General Axions

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Anomaly free Standard Model couplings

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- Electromagnetism: $\left(\frac{a}{f_a} F\tilde{F}\right)$
- Nuclear Force: $\left(\frac{a}{f_a} G\tilde{G}\right)$ — QCD Axion
- Nuclear Spin: $\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu \gamma_5 N\right)$ — General Axions

Spin 1

Anomaly free Standard Model couplings

- Nuclear Spin: $\left(\frac{F'_{\mu\nu}}{f_a} \bar{N}\sigma^{\mu\nu} N\right)$ — Dipole moment
- Electro-magnetism: $\left(\epsilon F' F\right)$ — Kinetic Mixing
- Nucleon Current: $\left(g A'_\mu J^\mu_{B-L}\right)$ — B-L

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$$\text{Dark Matter} \implies a = a_0 \cos\left(m_a t\right)$$

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Current Searches

(m_a ~ GHz)

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This Talk

Cosmic Axion Spin Precession Experiment (CASPEr)

with

Dmitry Budker
Peter Graham
Micah Ledbetter
Alex Sushkov

PRX **4** (2014) arXiv: 1306.6089
PRD **88** (2013) arXiv: 1306.6088
PRD **84** (2011) arXiv: 1101.2691

CASPEr: Axion Effects on Spin

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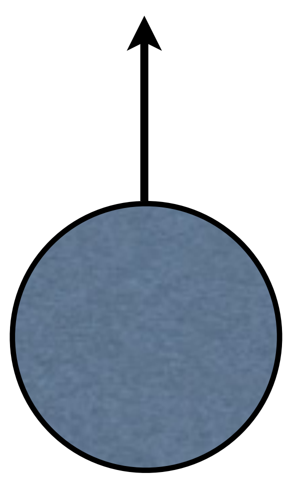
General Axions

Neutron



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Neutron in
Axion Wind

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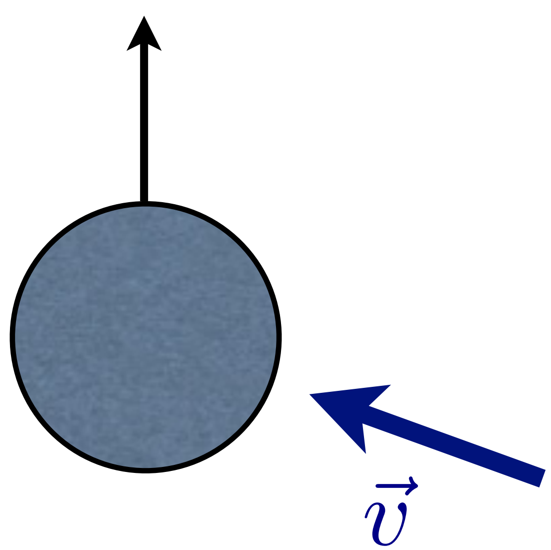

$$H_N \supset \frac{a}{f_a}\vec{v_a}.\vec{S}_N$$

Spin rotates about
dark matter velocity

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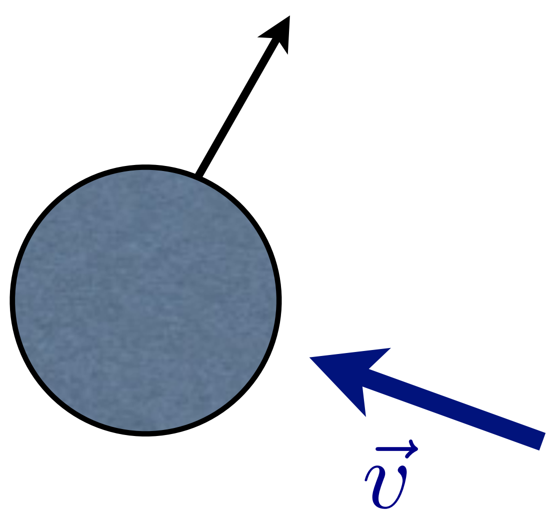

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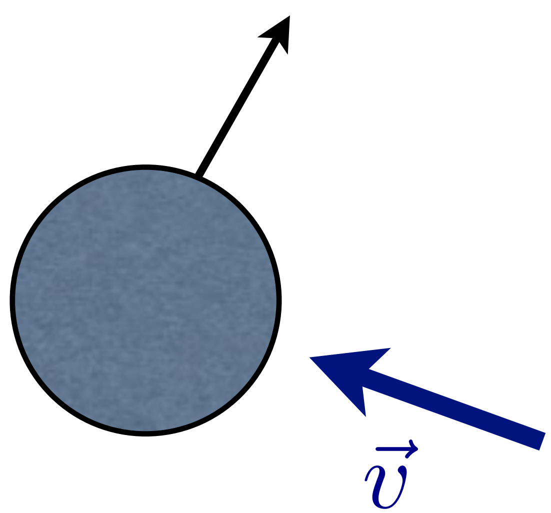

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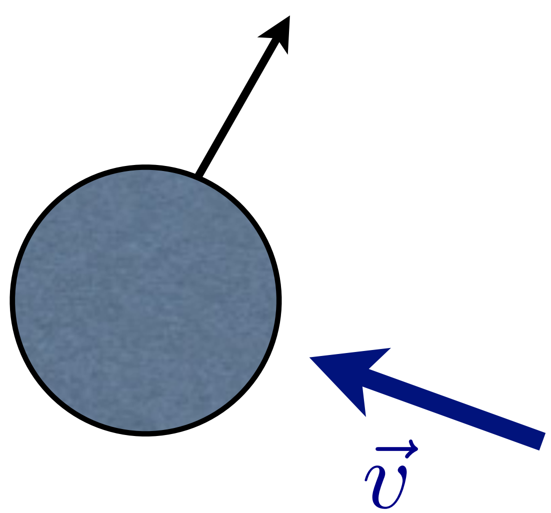

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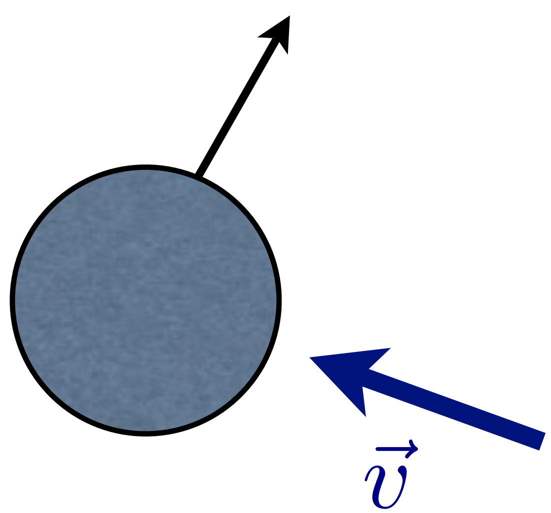

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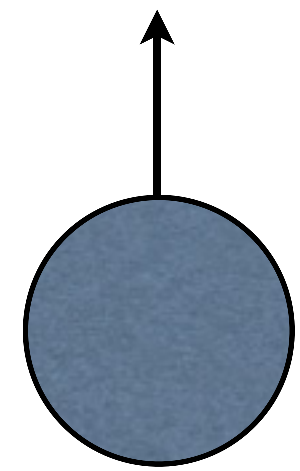

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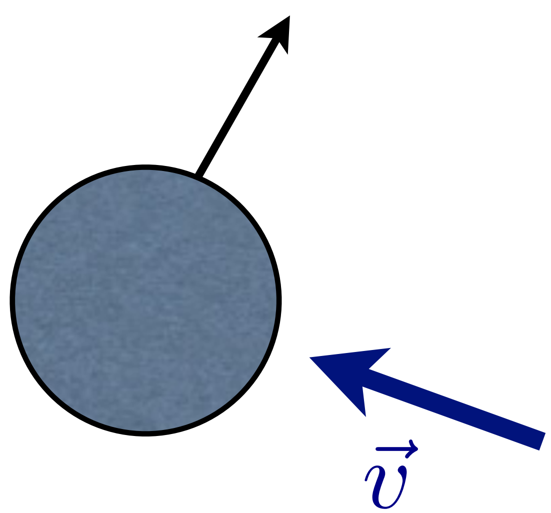

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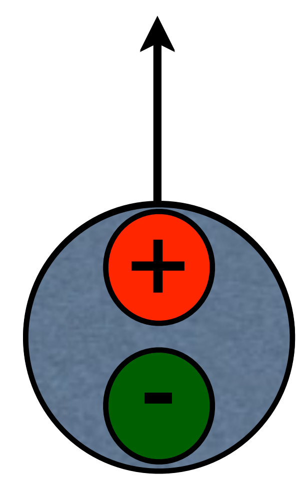
Neutron in
QCD Axion Dark Matter



$$\left(\frac{a}{f_a}G\tilde{G}\right)$$

QCD axion induces electric dipole moment
for neutron and proton

Dipole moment
along nuclear spin

Oscillating dipole: $d \sim 3 \times 10^{-34}\,\cos\left(m_a t\right)\,e\,\mathrm{cm}$

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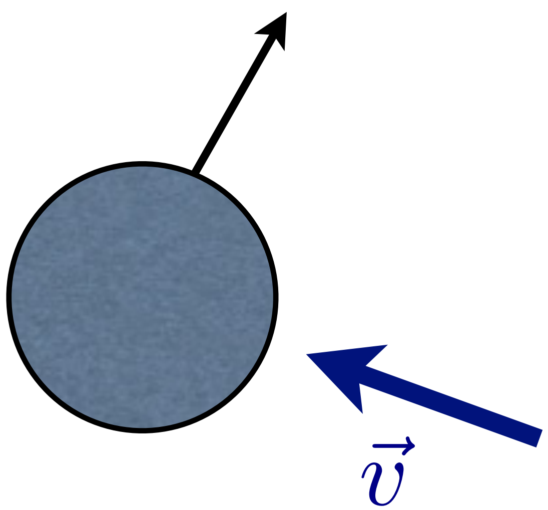

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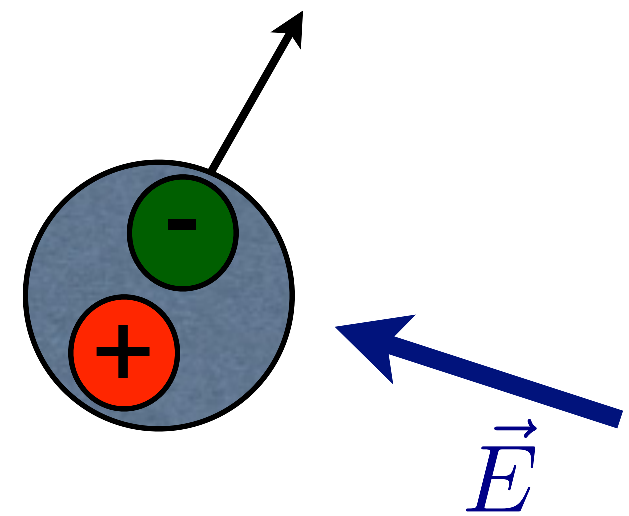

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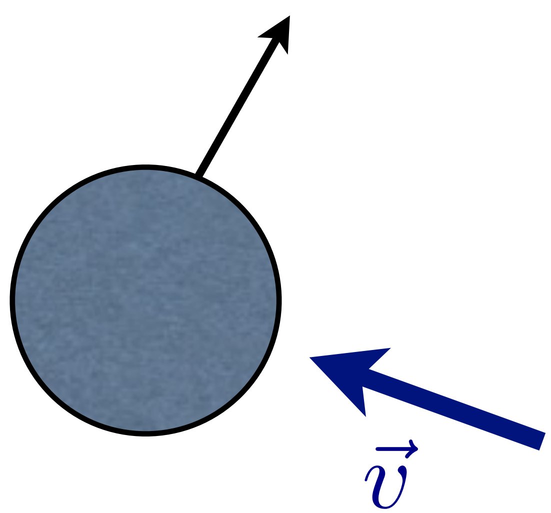

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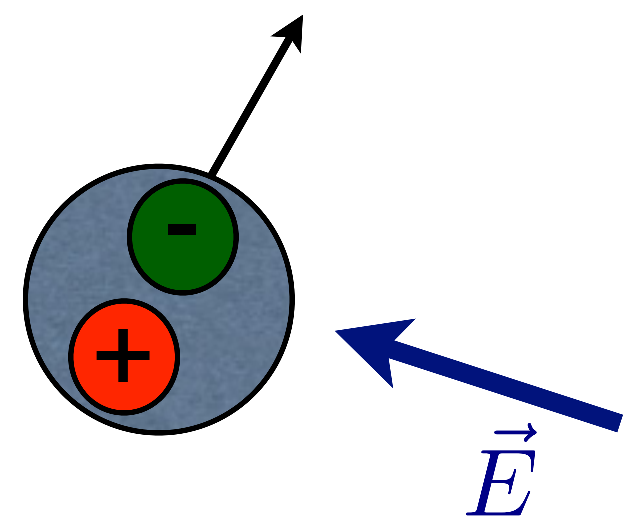

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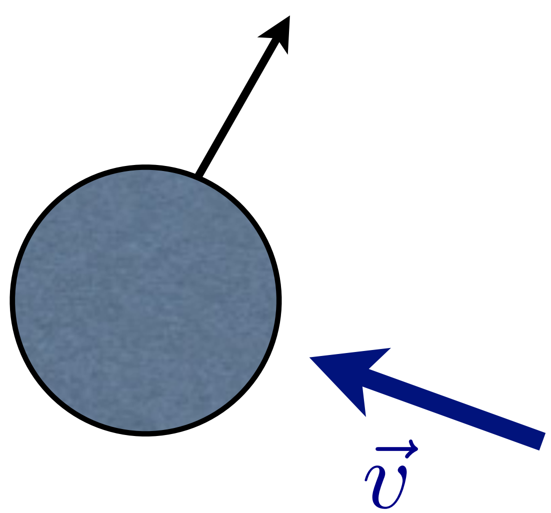

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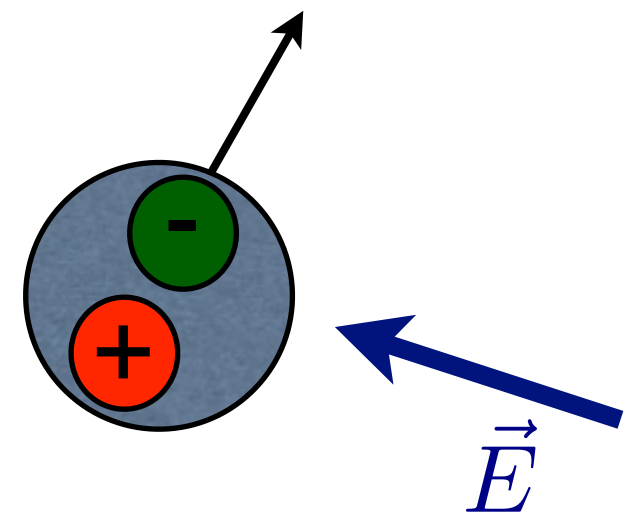
Measure Spin Rotation, detect Axion

QCD Axion

Neutron in QCD Axion Dark Matter



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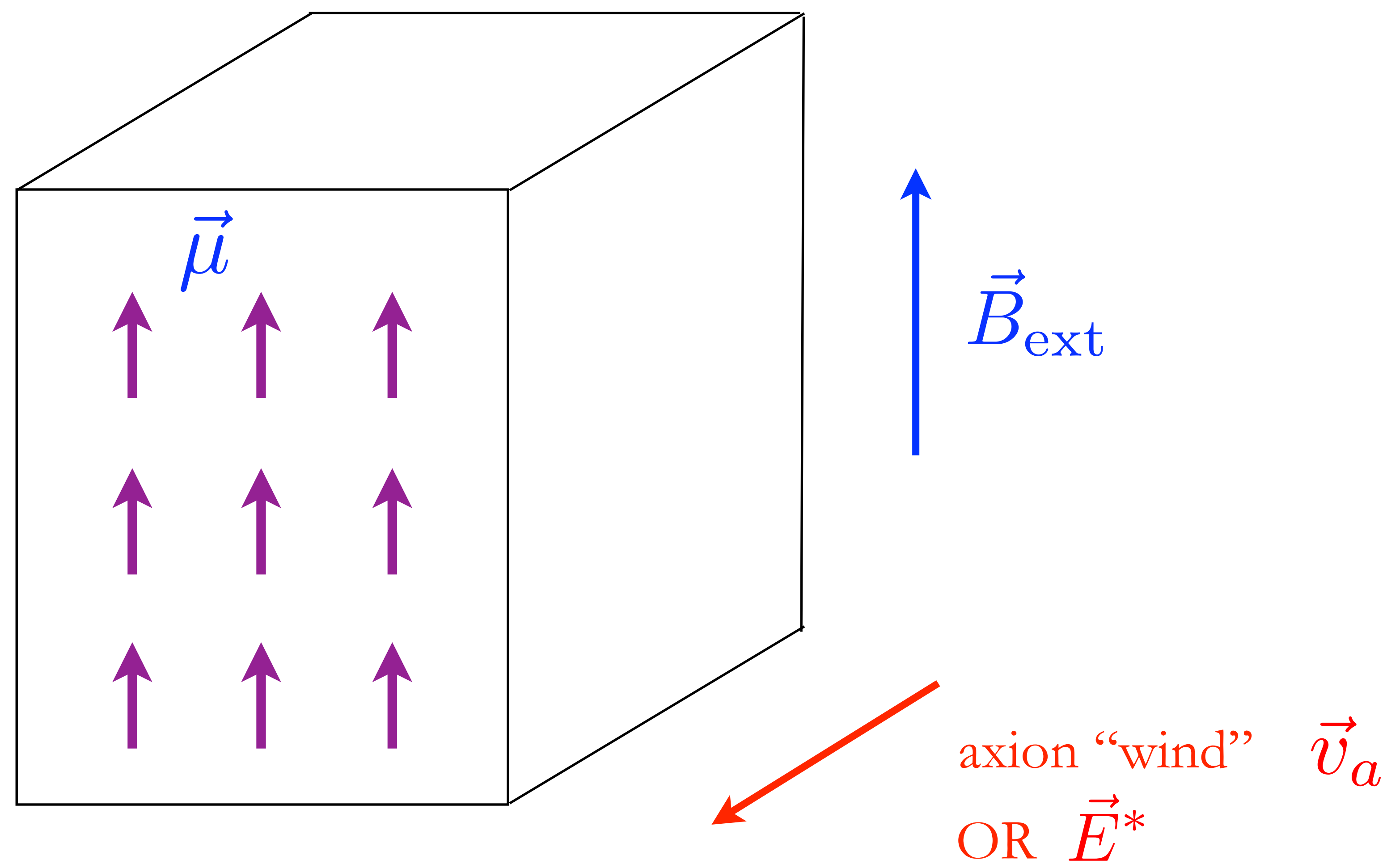
CASPEr

Axion affects physics of nucleus, NMR is sensitive probe



Larmor frequency = axion mass ➔ resonant enhancement

CASPEr

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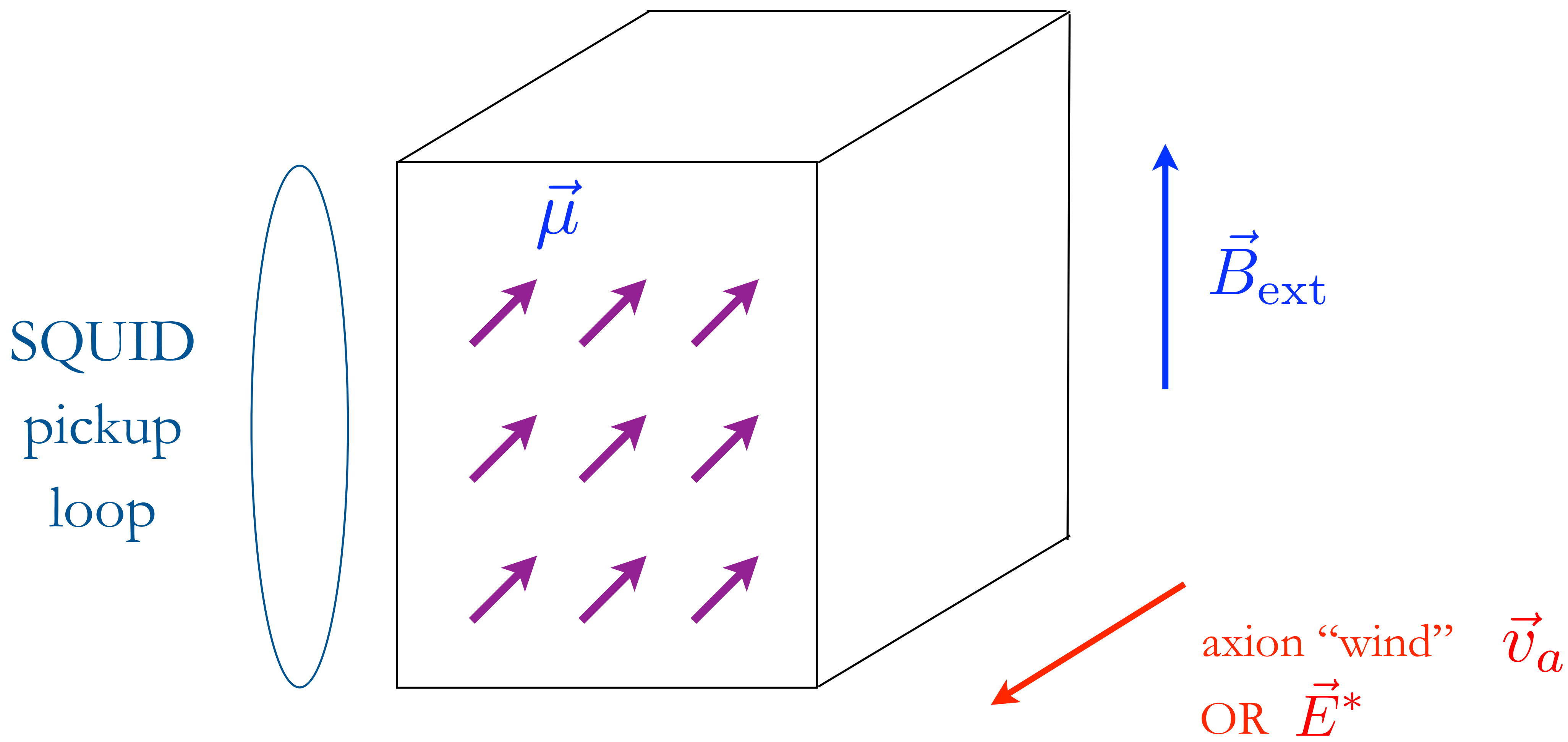


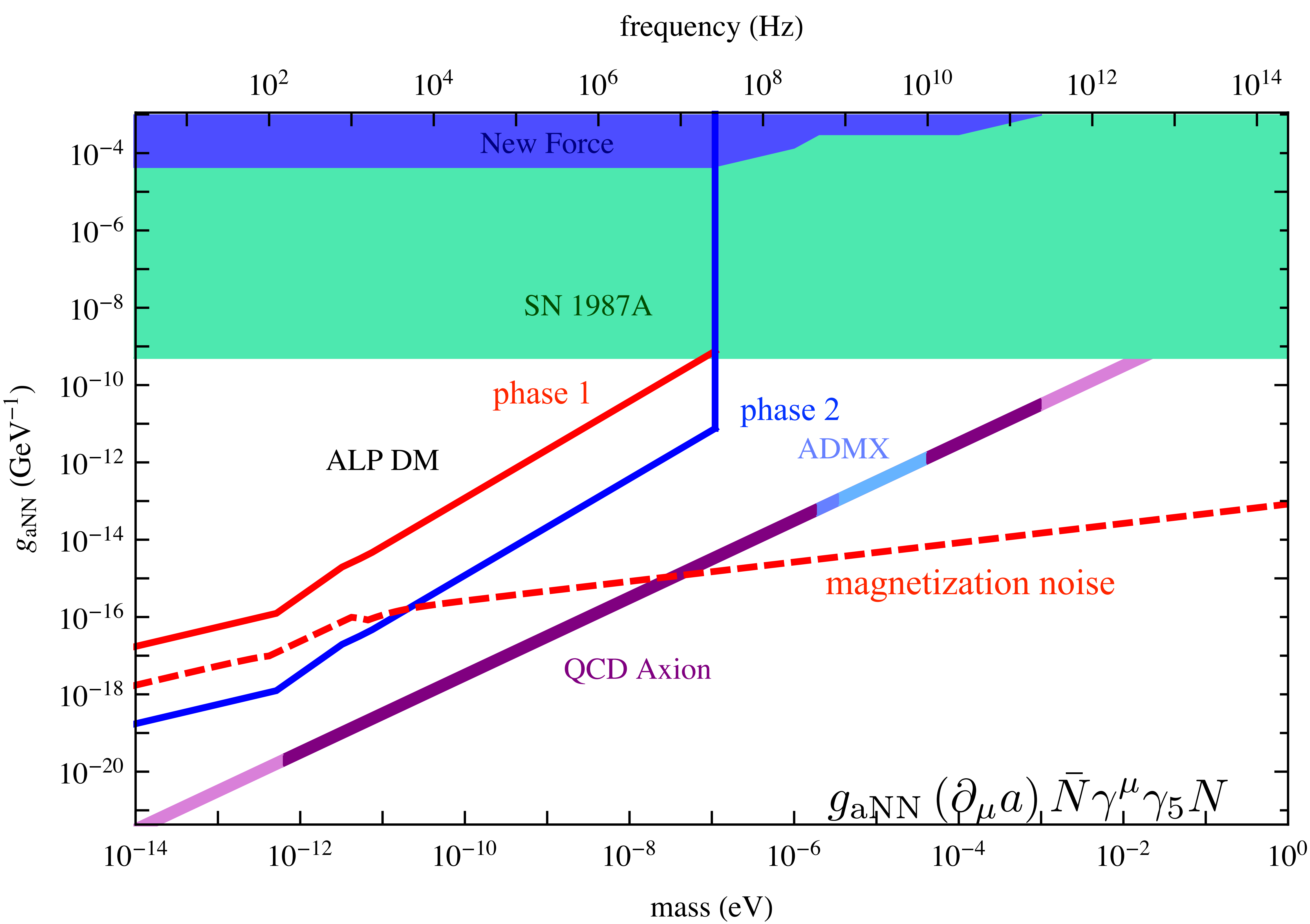
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

NMR well established technology, noise understood, similar setup to previous experiments

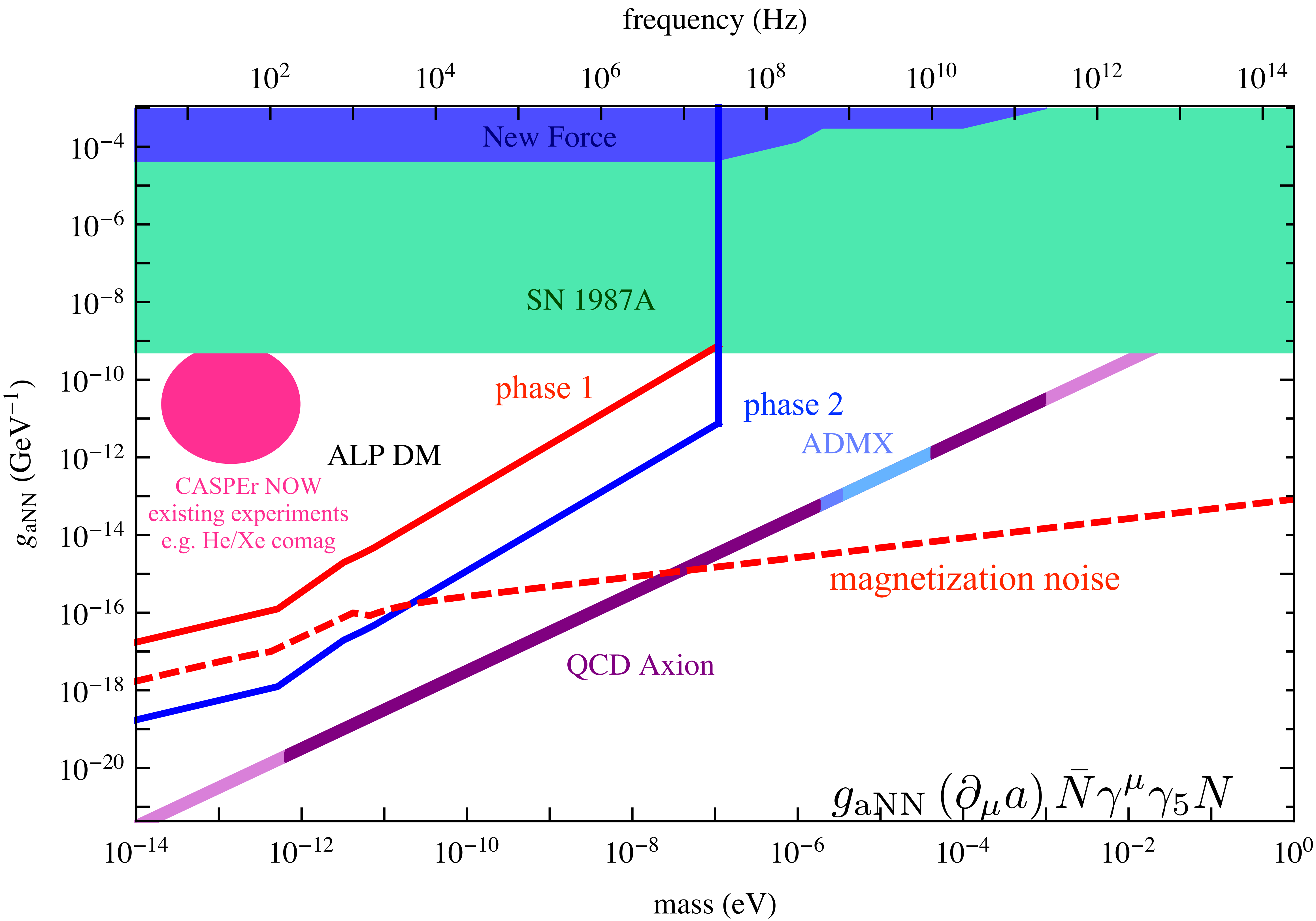
Example materials: LXe, ferroelectric $PbTiO_3$, many others

CASPEr-General Axions



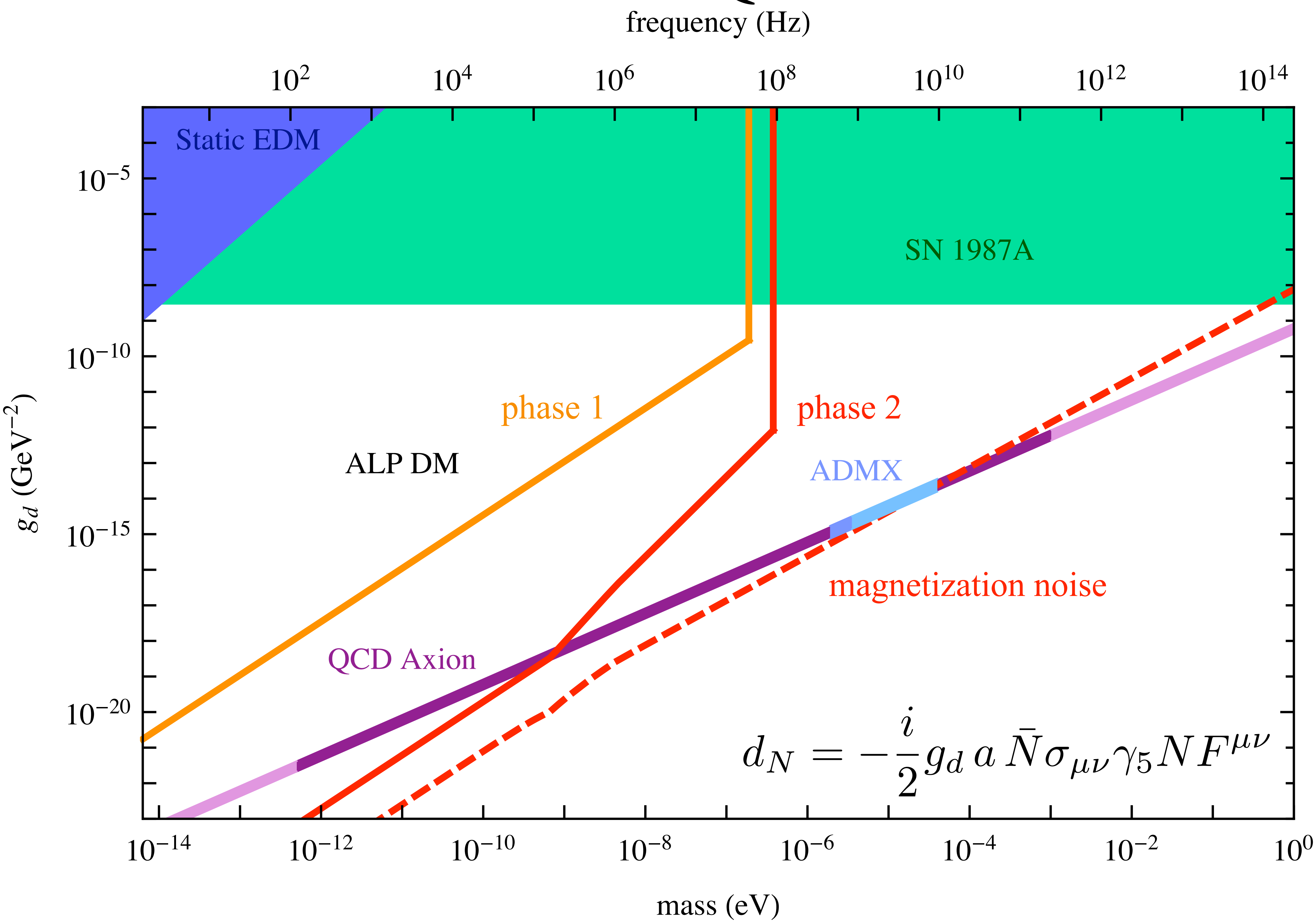
~ year to scan one decade of frequency

CASPEr-General Axions



~ year to scan one decade of frequency

CASPEr-QCD Axion



Verify signal with spatial coherence of axion field

Dark Photon Detection with a Radio

with

Peter Graham
Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Yue Zhao

arXiv: 1411.7382

Dark Photon Dark Matter

Many theories/vacua have additional, decoupled sectors, new U(1)'s

Natural coupling (dim. 4 operator): $\mathcal{L} \supset \varepsilon F F'$

mass basis:

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - eJ^\mu_{EM}\left(A_\mu + \varepsilon A'_\mu\right)$$

photon with small mass and suppressed couplings to all charged particles

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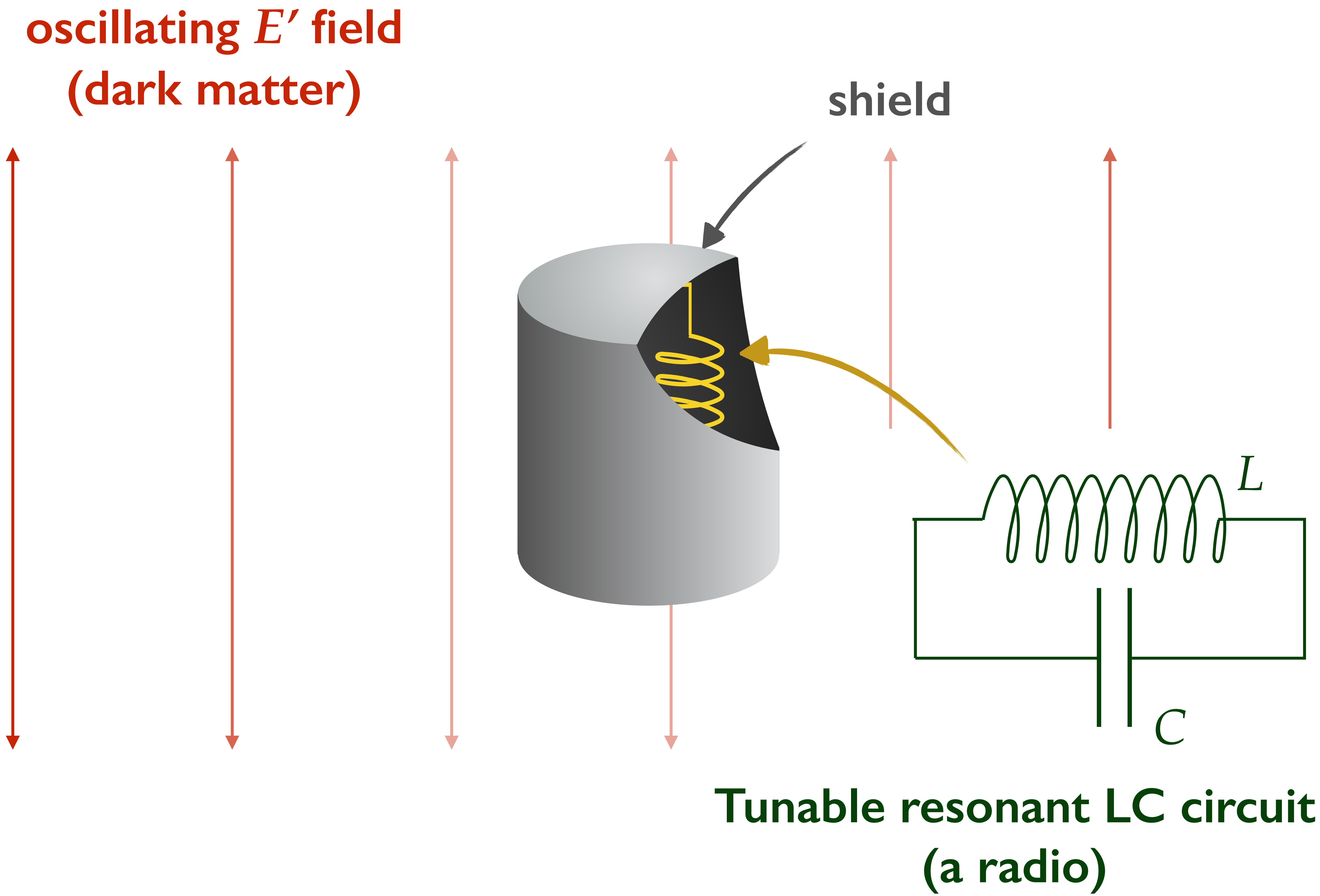
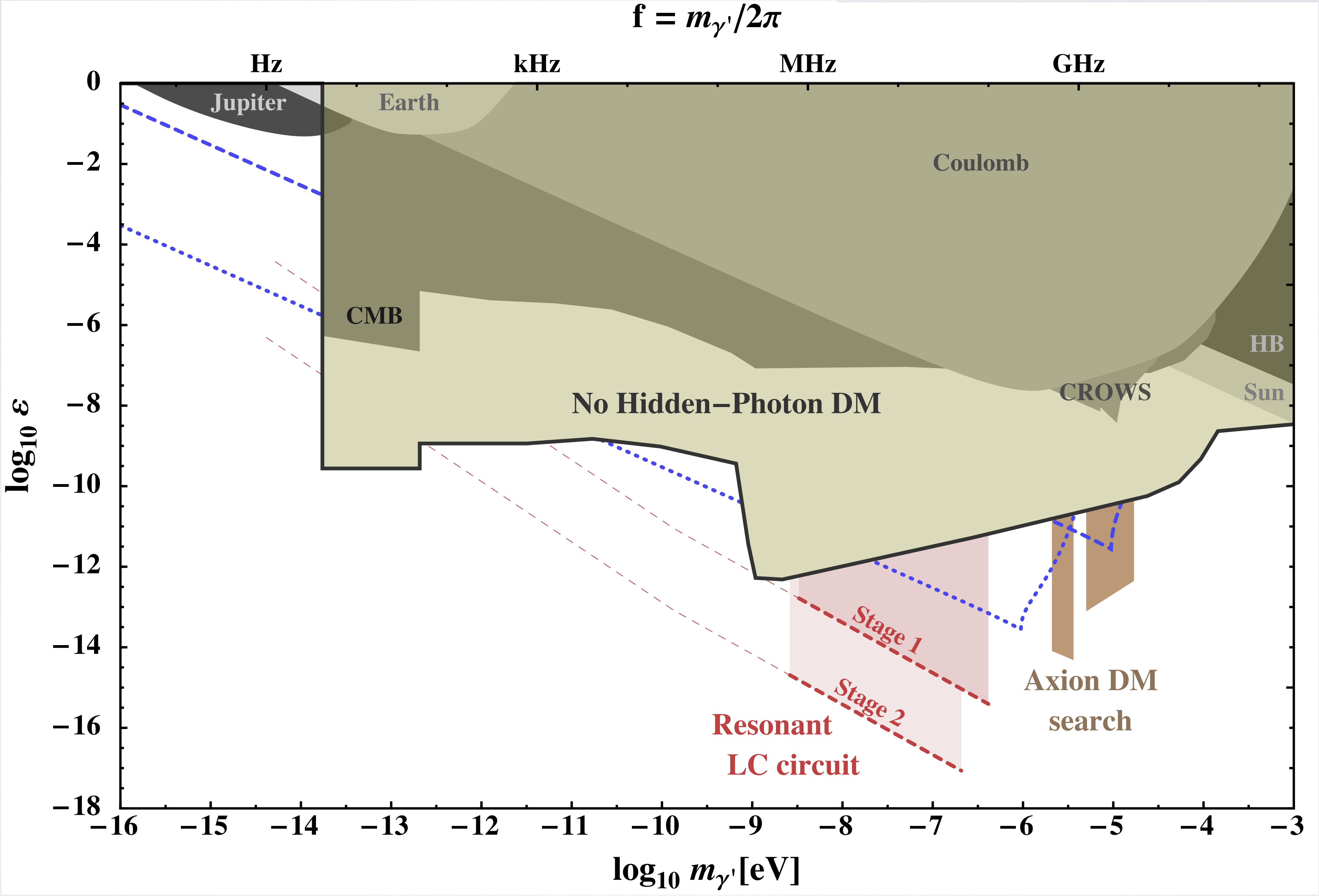
can drive current behind EM shield

Dark Matter Radio Station



EXPECTED REACH

Stage 1: size ~50 cm, T= 4K, Q=10^6, 1 year scan



Stage 2: size ~1 m, T= 10mK, Q=10^6, 1 year scan

B-L Dark Matter with Accelerometers

(under development)

with

Peter Graham
David Kaplan
Jeremy Mardon

B-L Dark Matter

Other than electromagnetism, only other anomaly free standard model current

$$\mathcal{L} = -\frac{1}{4}\left(F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - gJ^\mu_{B-L}A'_\mu$$

Protons, Neutrons, Electrons and Neutrinos are all charged

Electrically neutral atoms are charged under B-L

Force experiments constrain g < 10^{-21}

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can accelerate atoms

B-L Dark Matter

Acceleration Per Baryon: $\dfrac{gE'}{m_n} \sim 10^{-10}\,\dfrac{\mathrm{m}}{\mathrm{s}^2}\left(\dfrac{g}{10^{-21}}\right)$

Atomic Accelerometers $\gtrapprox 10^{-12}\dfrac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}$ (@ 1 Hz)

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Dark Matter force depends upon net neutron number

Time dependent equivalence principle violation!

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Time dependent equivalence principle violation!

Without extra work, Stanford facility probes $g \approx 10^{-26}$

Improvements possible with resonant schemes

Seems promising!

Conclusions

WIMPs

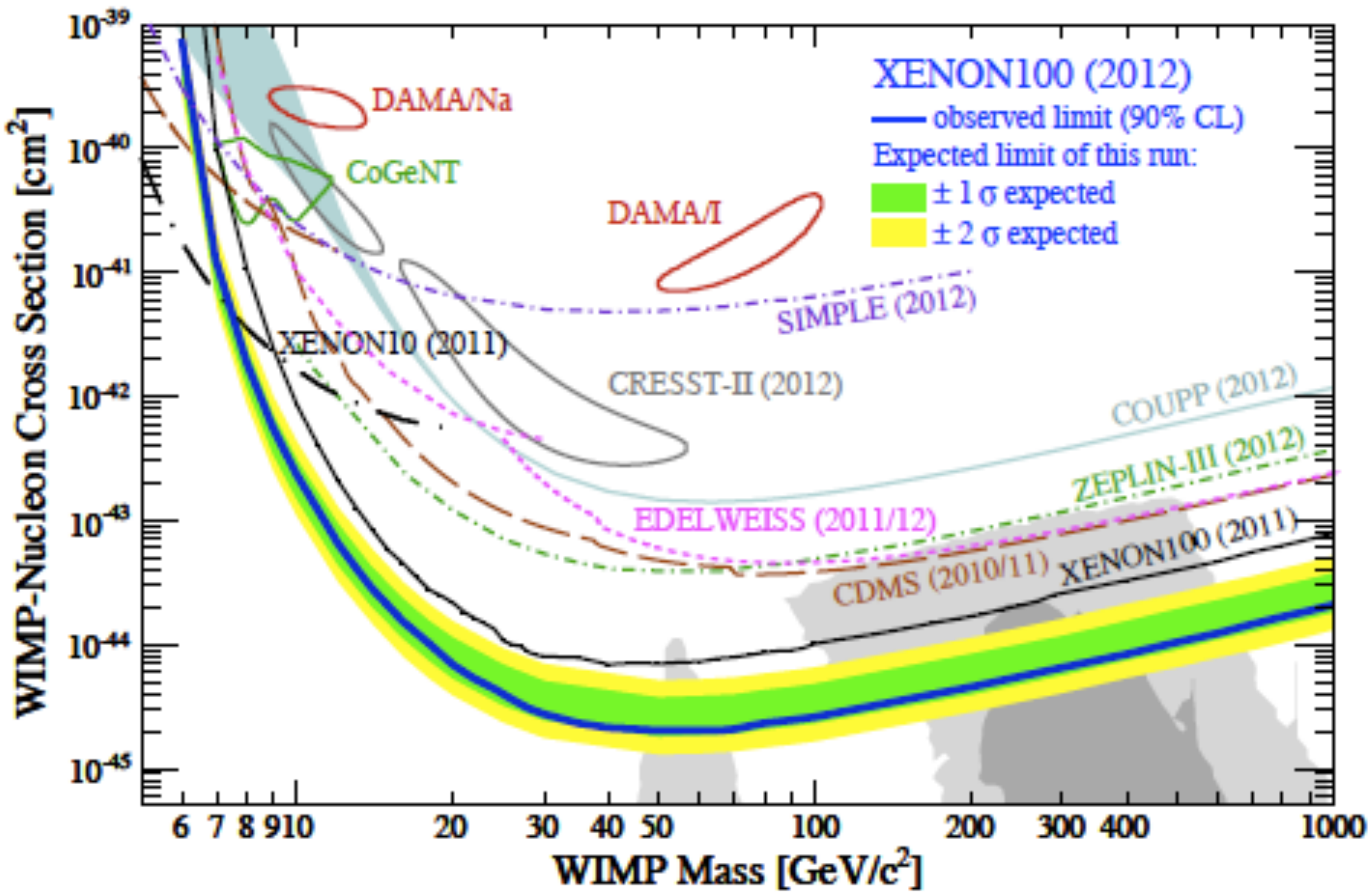
Scalable

Goodman & Witten (1985): $\sigma \sim 10^{-38}\,\mathrm{cm}^2$

Z

h

W



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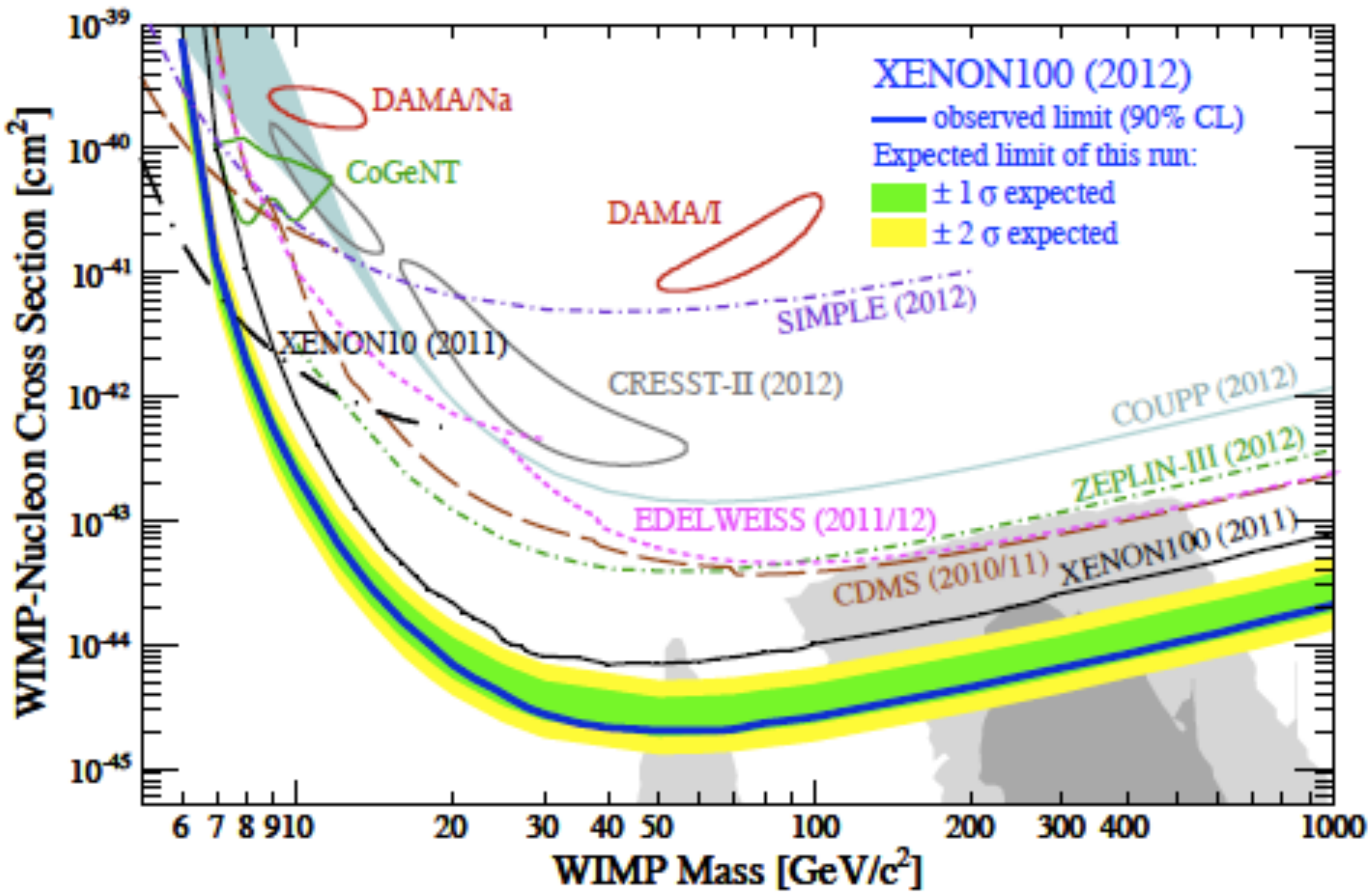
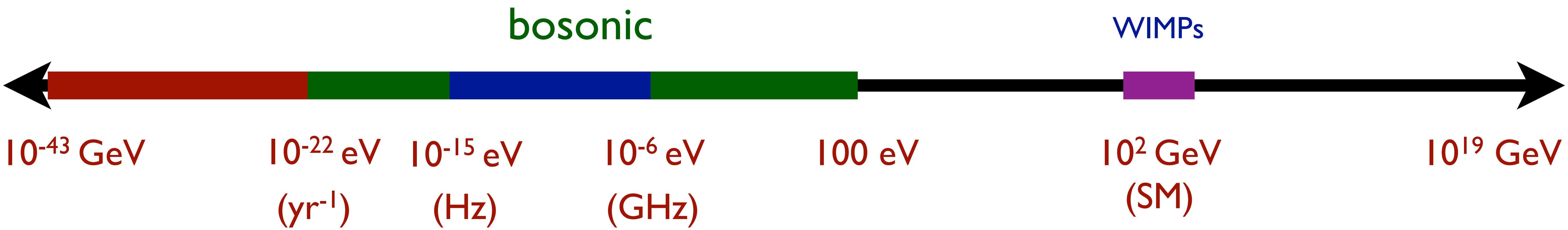


Similar approach seems possible in searching for oscillating fields

The Dark Matter Landscape



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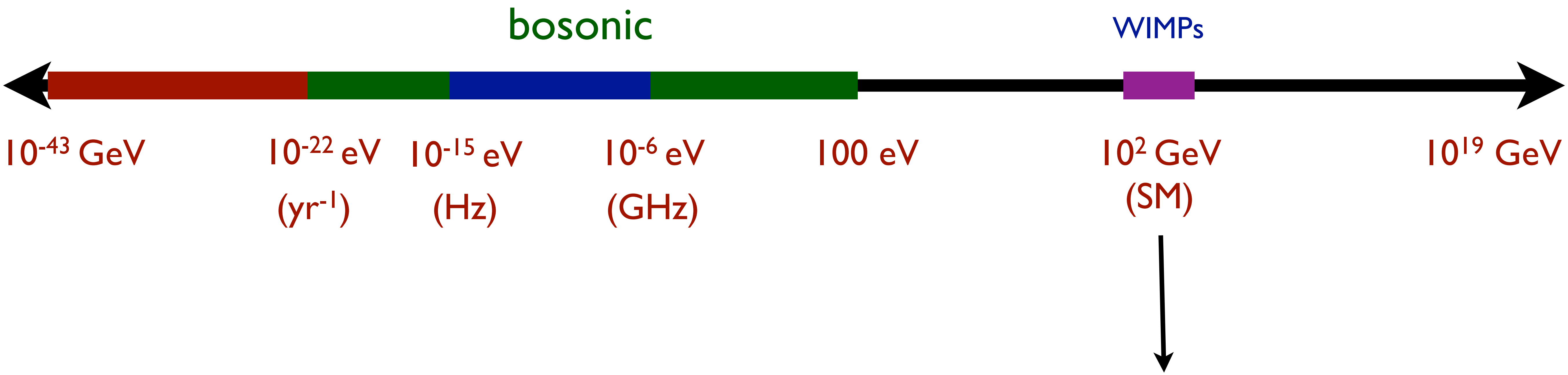
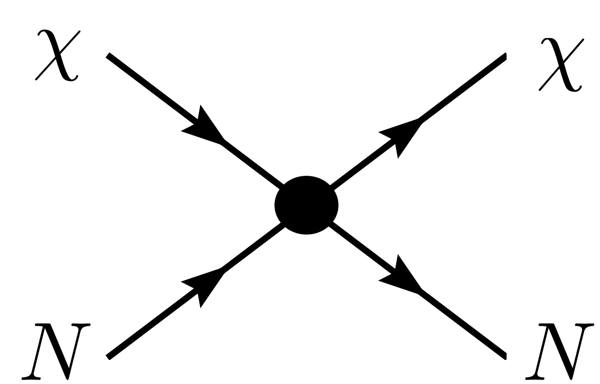


Search for single, hard particle scattering



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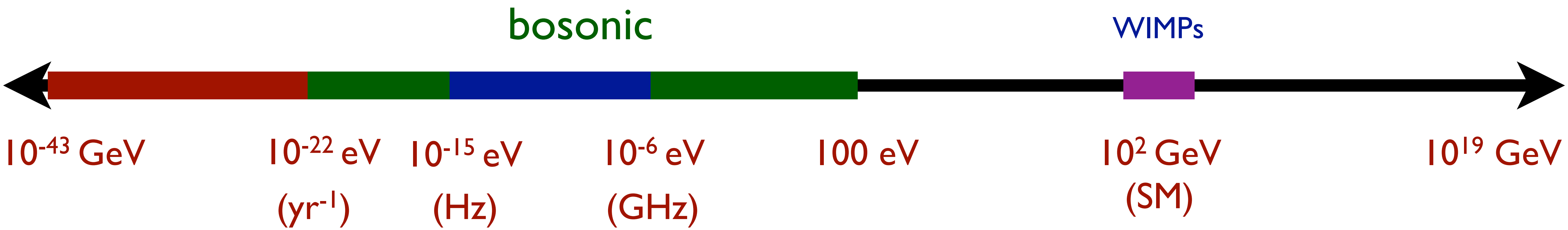


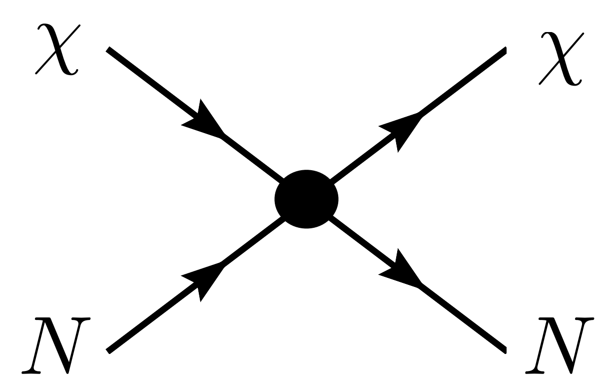
Time dependent moments of coherent classical field

Interactions restricted by symmetry

Frequencies can naturally be lab accessible (Hz - GHz)

Lab-scale experiments

Search for single, hard particle scattering



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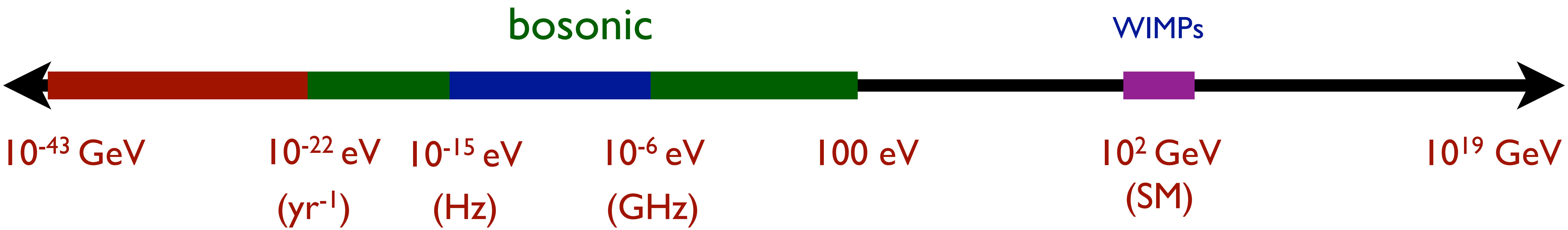

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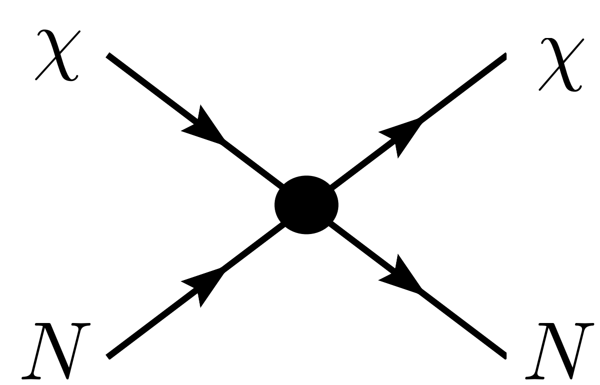

How do we cover full range?

Backup

A Different Operator For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta \, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \theta \, e \, \mathrm{cm}$

the axion: $\mathcal{L} \supset \dfrac{a}{f_a} G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \dfrac{a}{f_a} \, e \, \mathrm{cm}$

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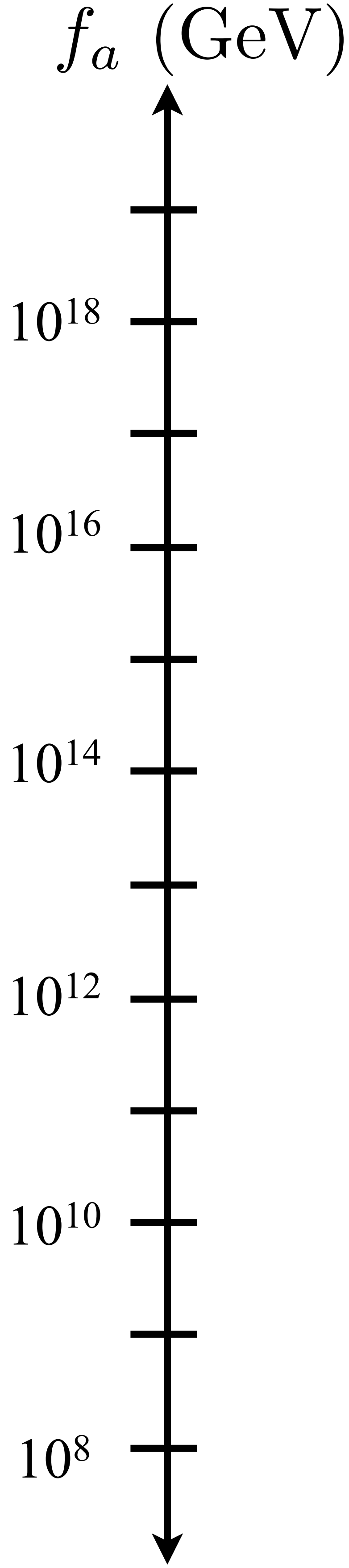
$$a(t) \sim a_0 \cos\left(m_a t\right) \quad \text{with} \quad m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$$

axion dark matter $\rho_{\mathrm{DM}} \sim m_a^2 a^2 \sim (200\mathrm{MeV})^4 \left(\frac{a}{f_a}\right)^2 \sim 0.3\, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

so today: $\left(\frac{a}{f_a}\right) \sim 3 \times 10^{-19}$ independent of f_a

axion gives all nucleons an oscillating EDM (kHz-GHz) independent of f_a,
a non-derivative operator

Constraints and Searches



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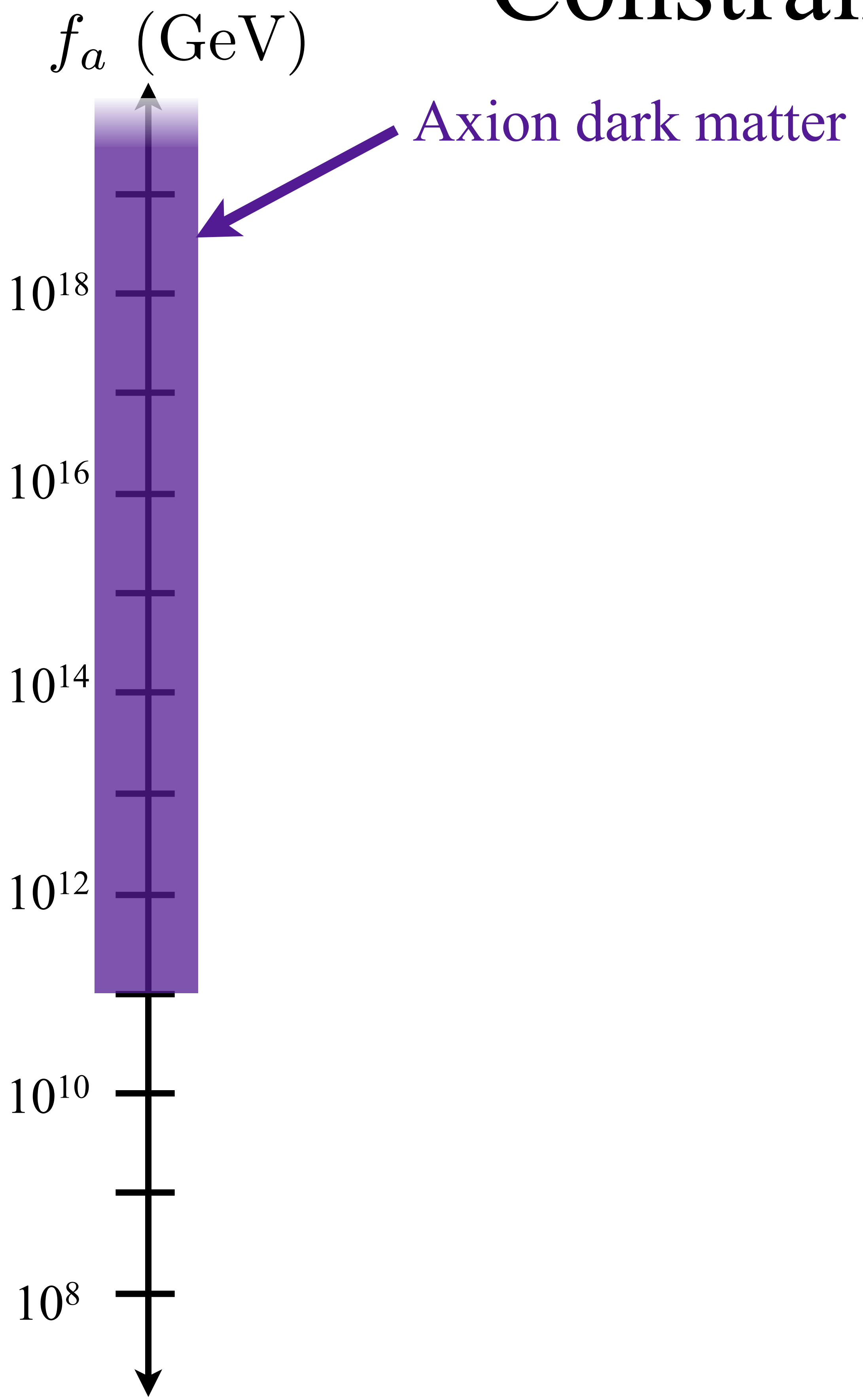

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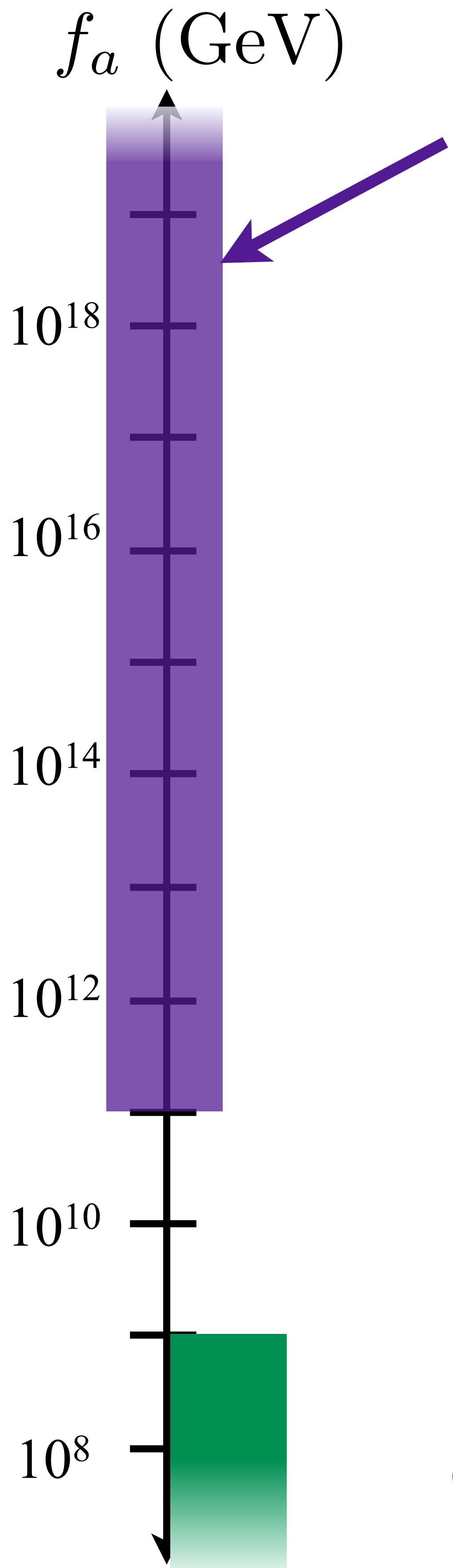
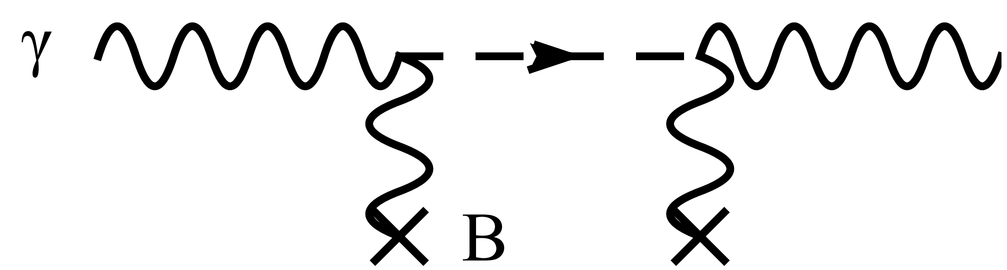


Axion dark matter

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$

laser experiments:



$\propto \frac{1}{f_a^4}$

axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST

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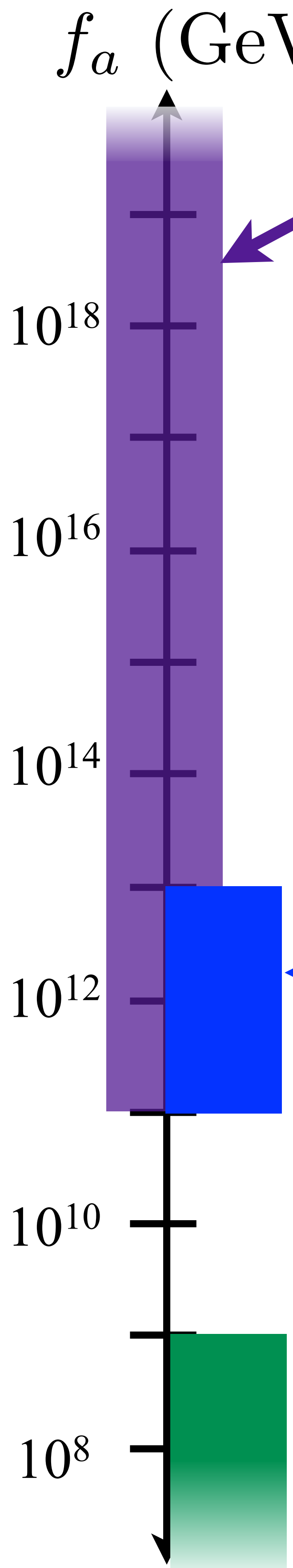

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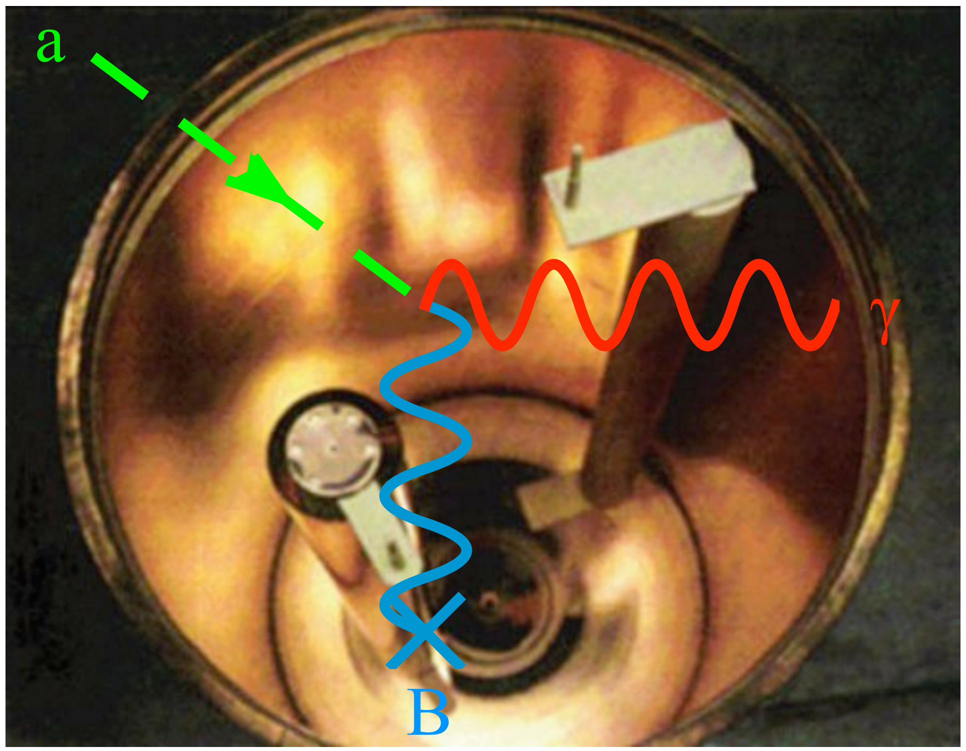

axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

size of cavity increases with f_a

signal $\propto \frac{1}{f_a^3}$

microwave cavity (ADMX)

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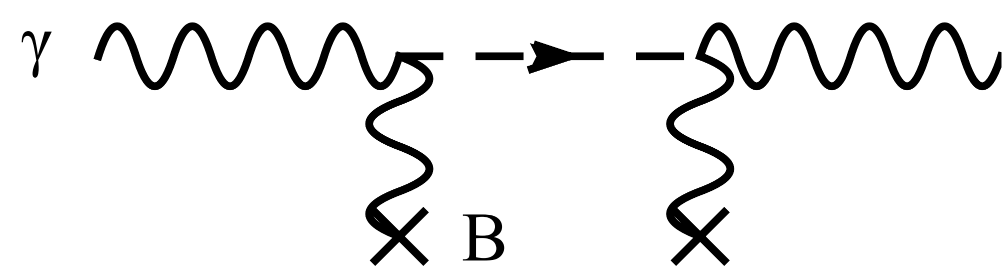

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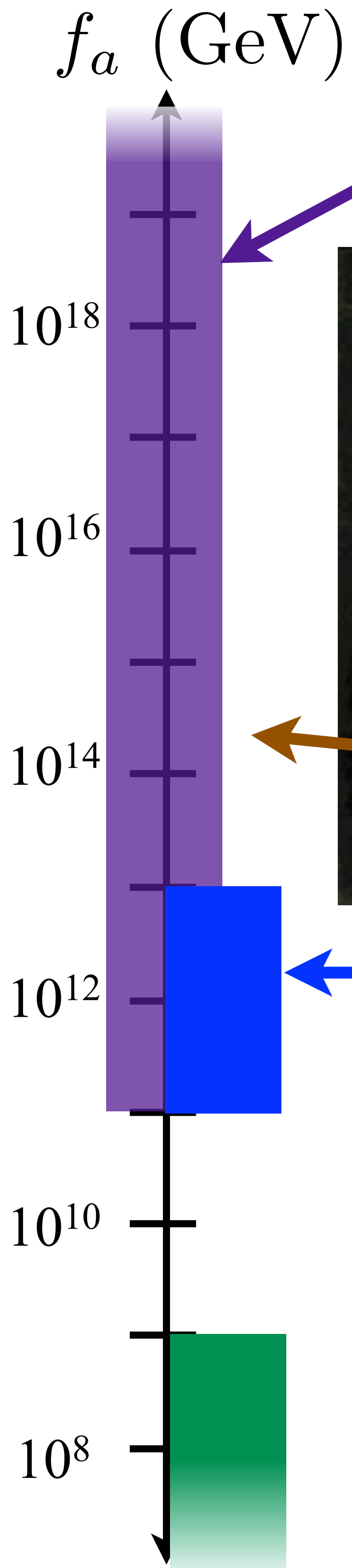

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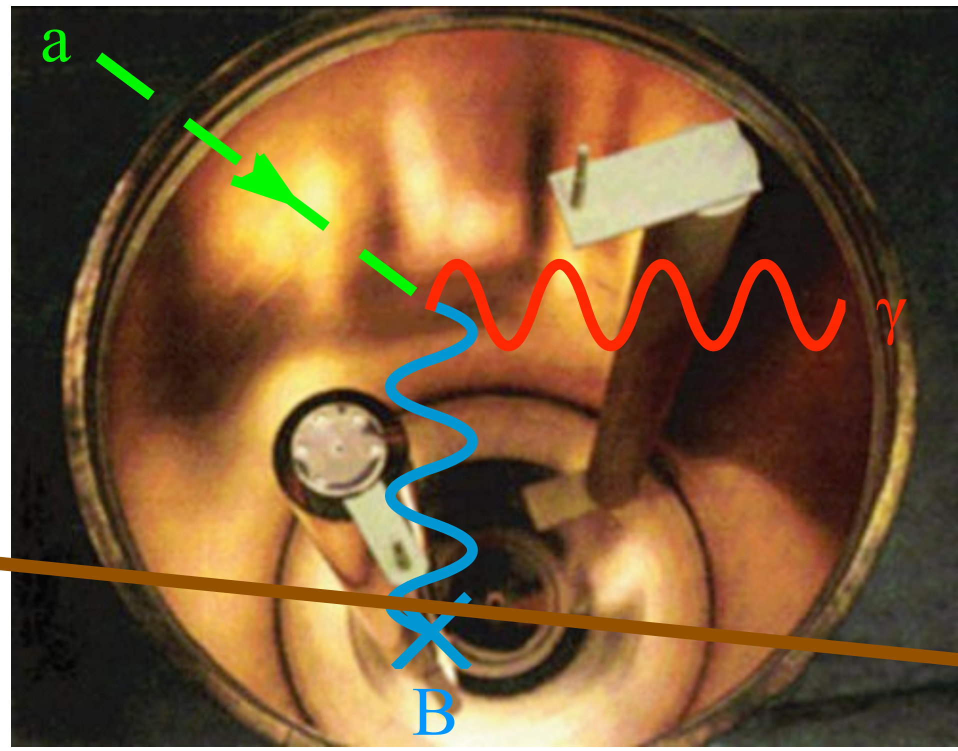

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S. Thomas

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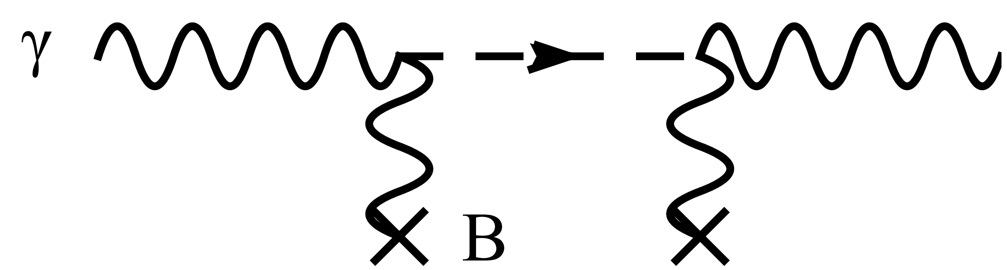

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Other ways to search for light (high f_a) axions?

Axions and the CMB

Assuming BICEP detected gravitational waves in the CMB (some tension with Planck):

$$H_{\rm inf} \sim 10^{14}\ \text{GeV}$$

if symmetry broken after inflation → topological defects (strings + domain walls), constrained by observations

if symmetry broken before inflation → inflation can induce isocurvature perturbations of axion, weak constraint on ALPs probed by CASPEr.

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for QCD axion, constrains **one** cosmological history.

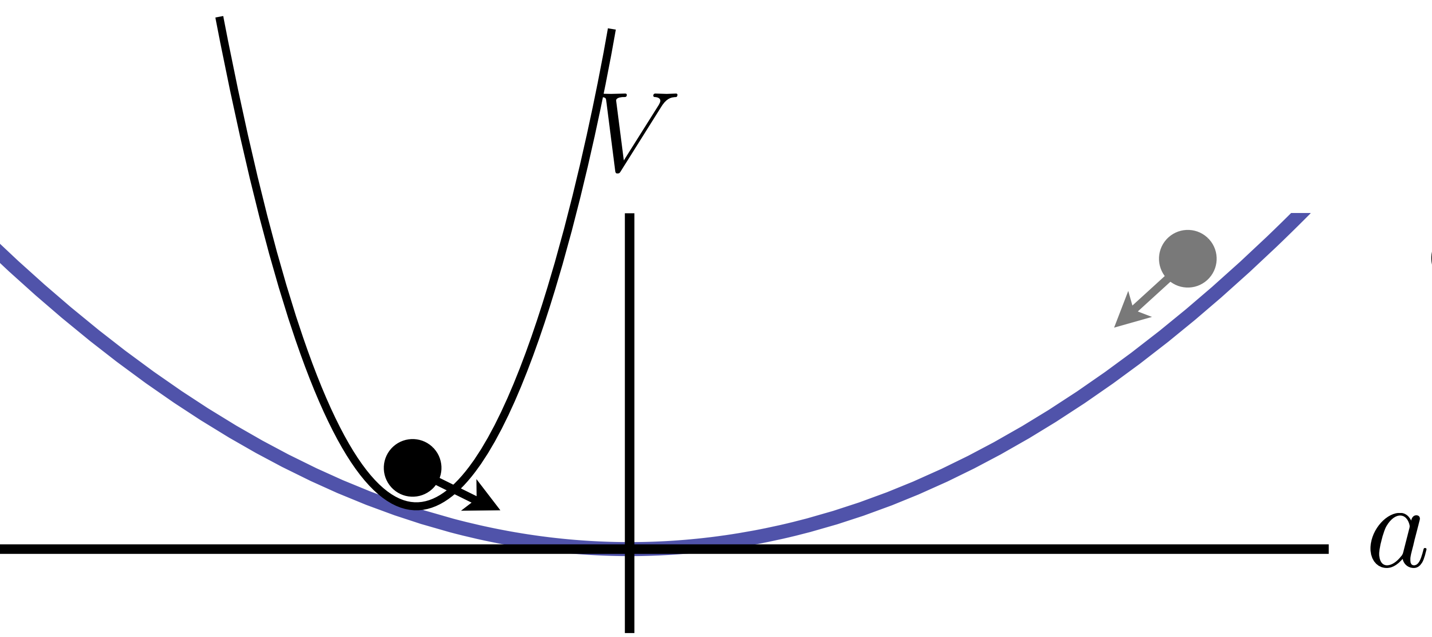
Requires knowing physics all the way up to GUT scale $\sim 10^{16}\ \text{GeV}$

many others possible.

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.

Need not be on during inflation.



Axion oscillates earlier, damps to high temperature minimum.

Misalignment of minima gives axion dark matter.

Dark matter from choice of parameters instead of initial conditions.

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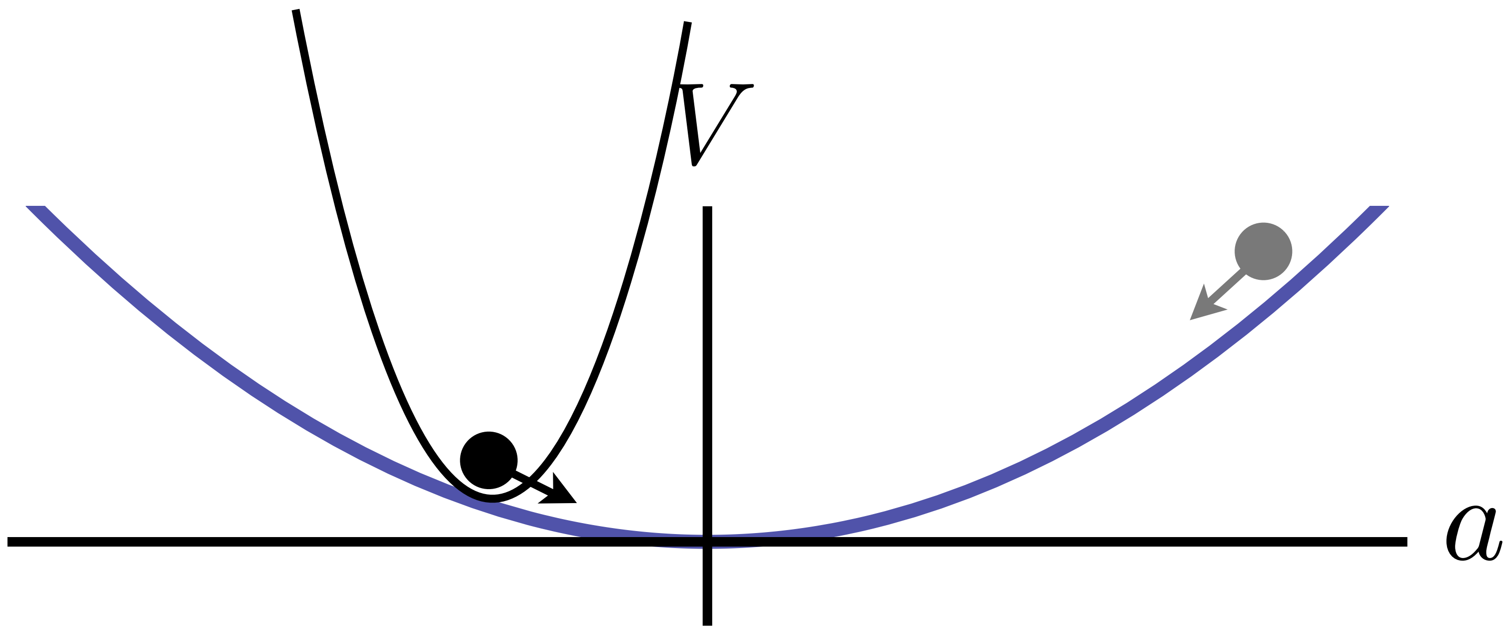

e.g. thermal monopole density, high temperature mass, and many others

Fischler & Preskill (1983)

e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

Bound depends upon high energy physics, while strong CP, axion dark matter rely upon low energy physics.

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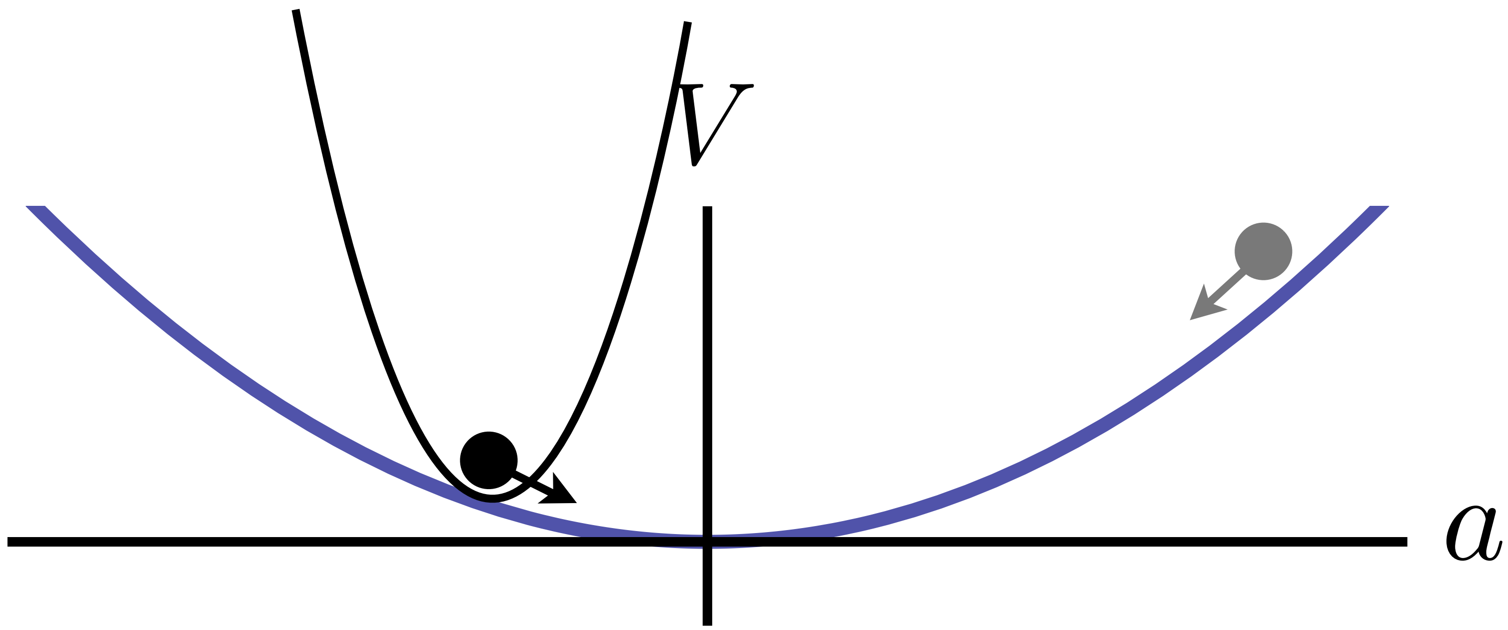

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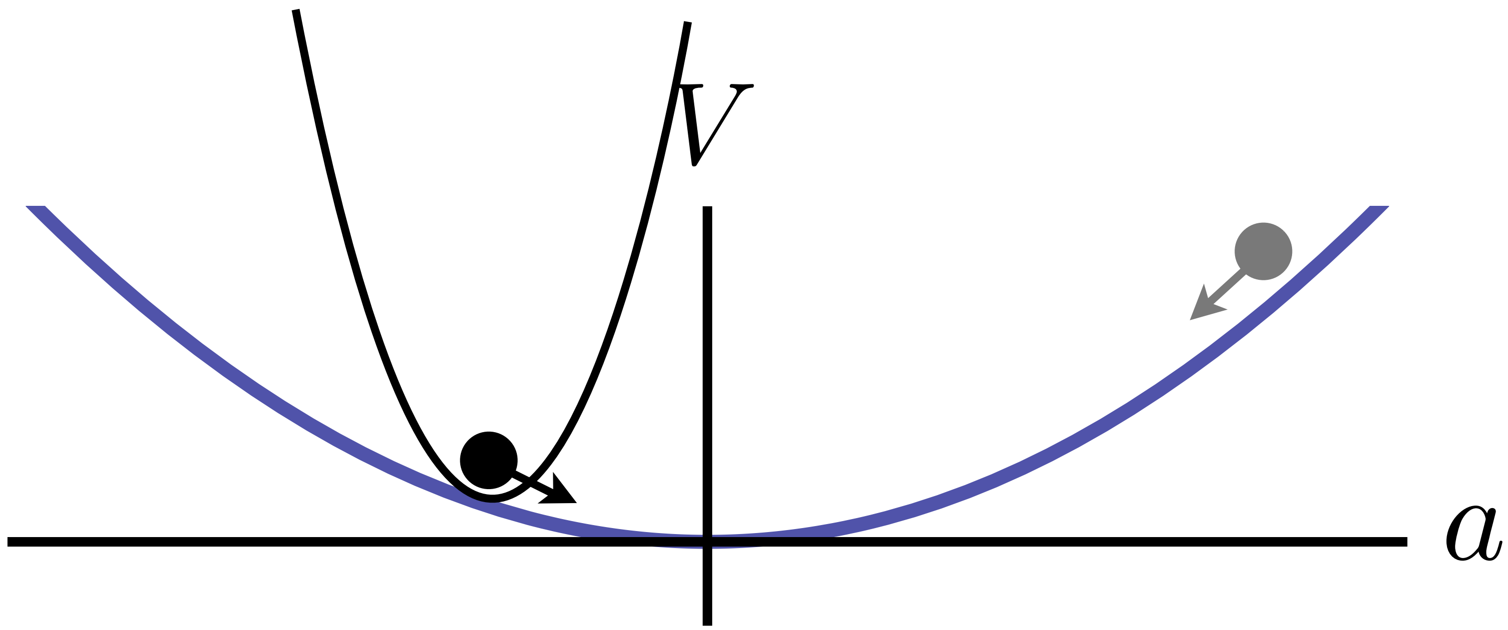

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